Scottish & Southern Electricity Networks

University of Strathclyde Engineering

NINES

2A Battery Operational Effectiveness

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List of acronyms

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
ACG	Active Network Management Controlled Generation
ANM	Active Network Management
BC	Binding Constraint
BESS	Battery Energy Storage System
BMS	Battery Management System
BUR	Burradale
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CTR	Constraint Rule
DECC	Department of Energy & Climate Change
DSM	Demand Side Management
EP	Electricity Price
ERDF	European Regional Development Fund
EROC	Energy-related Operating Cost
FES	Flywheel Energy Storage
FIT	Feed-in Tariff
IT	Information Technology
Li-ion	Lithium-ion
LK	Knowe
LPS	Lerwick Power Station
NAS	Sodium Sulphur
NEOC	Non-energy Operating Cost
NH	North Hoo
NiCd	Nickel Cadmium
NINES	Northern Isles New Energy Solutions
OPEX	Operational Expenditure
PCS	Power Conversion System
PHS	Pumped Hydroelectric Storage
PPA	Power Purchase Agreement
PSS/E	Power System Simulator for Engineering
SGS	Smarter Grid Solutions
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SSEN	Scottish and Southern Electricity Networks
SVT	Sullom Voe Terminal
SVTc	The minimum-take export limit of SVT
TES	Thermal Energy Storage
TGO	Total Generation Output
UoS	University of Strathclyde
VRB	Vanadium Redox Flow Battery
VRLA	Valve regulated lead-acid
ZnBr	Zinc Bromine

Contents

Scottish & Southern Electricity Networks

List of Figures

Scottish & Southern Electricity Networks

List of Tables

Executive summary

Scottish & Southern Electricity Networks

This report provides a detailed review of the operational effectiveness of a valve regulated lead-acid (VRLA) Battery Energy Storage System (BESS) which has been installed as part of the NINES Project at Lerwick Power Station (LPS) on a distribution network operated by Scottish and Southern Electricity Networks (SSEN) in Shetland. The grid-scale VRLA BESS plays an important role in the time-shifting of conventional generation and renewable energy on the Shetland network.

The 1MW, 3MWh BESS had been integrated with an Active Network Management (ANM) system which manages operation of all devices connected via the NINES Project on the Shetland network. The ANM system calculated schedules were employed over four months from February to May 2015 to schedule the battery to lop peaks and fill troughs in the demand curve, and to alleviate the constraints on non-firm intermittent generation. From June 2015 the BESS was manually scheduled to discharge at peak times and charge at times of low demand. Manual intervention was required due to issues with the ANM calculated schedules which resulted in an unsatisfactory utilisation of the battery (47.2% evaluated exclusive of outages). Based on outputs of the BESS in the first full year, the manual schedules were evaluated and found to achieve a higher utilisation of the battery (86.1%) than the ANM calculated schedules. Given the 1MW, 3MWh BESS was expected to complete 300 full cycles and discharge 0.9GWh per annum, 96% of the expected number of cycles and 70% utilisation of the BESS were achieved in the first full year.

The discharge/charge cycle of the battery smoothed the demand curve of the Shetland network, which led to flatter power outputs and a more efficient operation of conventional generating plant. Between September 2014 – when the BESS was fully commissioned – and November 2016, the VRLA BESS absorbed 1.77GWh at off-peak times and discharged 1.34GWh during peak demand periods with an average round-trip efficiency of 75.7%, demonstrating the BESS was operating with a satisfactory performance in terms of efficiency.

Shetland has rich and various renewable energy resources. The export of non-firm renewable generation, i.e. ANM Controlled Generation (ACG), on the Shetland network were limited by a set of constraint rules (CTRs) so as to preserve the stability of the network. Under the up-to-date CTRs, charging the battery can increase the limit for ACG export providing additional headroom for ACG to generate. ACG curtailment that coincides with the increase in the ACG limit from charging the battery would therefore be reduced. Though manual schedules were not optimised for reducing ACG curtailment, around 52.7MWh of additional ACG export had been delivered to the network through charging the BESS over the period from September 2015 to November 2016 where the up-to-date CTRs were implemented. This reduction in ACG curtailment was less than the import of the BESS in the period evaluated. This was in part due to only 0.5MW ACG being connected until February 2016 when the ACG capacity increased to 3.5MW. During the period of review the export of 0.5MW ACG was rarely curtailed which affected the battery's ability to alleviate the ACG curtailment.

To maximise the benefit of the BESS and promote the utilisation of intermittent generation, a new real-time algorithm has been developed under the existing control architecture to schedule the battery to charge in direct response to the ACG curtailment. The real-time algorithm was evaluated in this report based on a period of historic data during which the ACG export experienced a high level of curtailment. Under the real-time algorithm, the battery was charged at the same rate as the lower value of ACG curtailment or the maximum allowable charge rate. The electricity absorbed by the BESS would all be from additional ACG export which would otherwise be curtailed. The actual test of the real-time algorithm will be carried out in future work where the installed capacity of ACG has increased to 8.5MW.

Operating with the real-time algorithm, 4MWh ACG absorbed by the BESS (i.e. the reduction in ACG curtailment) would be converted into 3MWh discharged energy in a full cycle due to the 75% round-trip efficiency. Based on the estimates of conventional generational cost (£200/MWh) and renewable

generation cost (£75/MWh), a £90,000 saving may be achieved per year by the time-shifting of ACG based on the 1MW, 3MWh BESS completing the expected 300 cycles per annum. It is evaluated that the total savings would reach approximately 27% of the total project replication costs at the end of the 15th year. Taking into account the benefit associated with the time-shifting of ACG enabled by the BESS, the net cost of using the BESS to alleviate renewable energy curtailment would be £203.14/MWh in 15 years. In consideration of an approximate projection of 30.54% growth in annual average oil price from 2016 to 2018 that is the main influence on the conventional generation cost, the saving achieved by the time-shifting of ACG would increase to £144,900 per annum and the percentage of the total savings against the total project replication cost may reach approximately 43.4% in 15 years. Following the growth in the saving, the net cost of alleviating ACG curtailment would be decreased to £157.39/MWh.

This report will contribute to Learning Outcomes: *"LO1: How can a distribution system be securely operated with a high penetration of renewable generation", "LO2: What is the relationship between intermittent generation and responsive demand, including storage", "LO5: What is the impact of the low carbon network on domestic and industrial customers"* and *"LO6: To what extent do the new arrangements stimulate the development of, and connection to, the network of more renewable generation and reduce the area's reliance on fossil fuels".*

1

Introduction

1. Introduction

1.1 Project Background

In 2010, a licence obligation was put in place requiring Scottish and Southern Electricity Networks (SSEN) to present an Integrated Plan to manage supply and demand on Shetland. The Shetland Islands are not connected to the main GB electricity network and, as such, face unique electrical challenges – but also a unique opportunity to decarbonise supply. Under the licence condition, this Integrated Plan was required to demonstrate that it had identified a solution based on the lowest lifecycle costs, taking into account its environmental obligations.

As part of the Integrated Plan submission, consideration was given to: the upgrading or replacement of Lerwick Power Station, the impact of third party generation requirements, the abundance of renewable energy resources, and the future demand on Shetland. The factors influencing the supply and demand issues on Shetland necessitated an innovative approach to their management. However, with innovation comes the need to trial solutions. As a result, SSEN originally proposed to split the implementation of the Integrated Plan into two phases:

Phase 1 (Northern Isles New Energy Solutions 'NINES') – implementation of the infrastructure necessary to actively manage demand, generation, reactive compensation and energy storage assets. These elements were coordinated to maximise the amount of energy harvested from renewable generation while maintaining supply quality and security. In doing so, two principal effects are achieved:

- a reduction in maximum demand; and
- a reduction in the electricity units generated by fossil fuels

Phase 2 (Shetland Repowering) – upgrading or replacement of Lerwick Power Station taking into account the learning acquired during Phase 1 and, where appropriate, extending the Phase 1 technology.

1.2 NINES Elements

NINES was designed and developed to operate in conjunction with Lerwick Power Station with the main aim of informing the optimum repowering solution. Whilst its primary objective was to trial 'smart grid' initiatives, importantly NINES has delivered funded elements and infrastructure that are expected to endure as part of, or alongside, the Shetland new energy solution. Central to the project has been the creation of an integrated set of models designed to anticipate the impact of NINES, covering the following themes:

- Dynamic stability model
- Steady state model
- Unit scheduling model
- Customer demand forecast model
- System development optimisation model
- Strategic risk and operational risk model
- Shetland economic model
- Commercial model

The aims of NINES have been to increase understanding of:

1. How best to accommodate Shetland's significant wind potential on a small distribution network; and
2. How the existing and known future demand on the island can be securely managed on a constrained, isolated system.

These models predict the behaviour of the energy systems on Shetland, and served to validate each of the key elements of NINES as they were added. Following this validation process, these models have been used to inform the development of the New Energy Solution realised through the competitive process. Through the successful operation of NINES, the infrastructure and knowledge to reduce the peak capacity requirement for any replacement solution to a level dependent on the particular assets connected, and the characteristics of the new solution have been determined. The NINES project assets are described below.

1. 1MW, 3MWh BESS at Lerwick Power Station
A 1MW, 3MWh battery acts as an energy storage system on the Shetland Network. In addition to facilitating the connection of new renewables, the battery assists in the operation of the existing island network by helping to reduce conventional generations' contribution to meeting peak demand. The battery has helped to accommodate the connection of new renewable generation that would otherwise not have been able to connect.

2. Domestic demand side management with frequency response
As part of the wider NINES benefits, Hjaltland Housing Association contracted with Glen Dimplex to install advanced storage heating and water heating in 234 existing homes. These new storage and water heaters were provided through Hjaltland and ERDF funding and have been specifically designed to use a much more flexible electrical charging arrangement. This new charging arrangement is determined based upon the predicted demand, weather forecasts, availability of renewables and other network constraints. This initial roll out was intended to help gauge the effectiveness of storage and demand side response at the domestic level.

The heaters incorporate additional insulation to minimise heat loss and storage heaters are fitted with programmable timers and an integrated fan to allow users much better control of temperature and operating times compared to conventional storage and water heating systems. The new heating system is designed to be more efficient, while giving the customer full control of both temperature and operating time whilst allowing for charging at times that best suit the network.

Glen Dimplex developed the heaters to provide frequency response based on requirements issued by SSEN. The devices are capable of shedding load in response to a loss of generation in 350ms.

3. Renewable generation
Shetland has some of the richest renewable energy resources in Europe and there is significant interest on the islands to connect a range of new renewable generators. There is a mix of wind and tidal generators currently connected that range in scale from 45kW up to 4.5MW. Prior to NINES these generators could not connect to the network due to the underlying voltage and stability constraints. Connecting more renewable generation, which is unavoidably intermittent, would have exacerbated these problems.

To address this, NINES has trialled an Active Network Management system which has offered renewable connections to developers. In return, they are required to consent to being constrained when the system cannot accommodate their generation. The measures that have been developed and trialled under NINES are reducing this constraint by being able to actively provide demand when there is renewable resource available.

These arrangements would be necessary even if Shetland is to become electrically connected to the National Grid at some point in the future. Current SSEN ANM systems in Orkney and the Isle of Wight evaluate real-time thermal constraints of existing cables to calculate a limit on ACG export. Furthermore, if a single mainland link is damaged, this could result in a prolonged outage, which would mean that Shetland would once again be electrically islanded.

4. Active Network Management (ANM) system
The ANM system calculates constraint limits and uses the binding constraint to provide appropriate set points to ACG. At present a day ahead scheduling model uses forecast information and aggregated daily energy requirements to schedule controllable demand. By establishing controllable demand on the island, progress has been made in exploiting and maximising Shetland's wind generation potential on an islanded basis, and in reducing the generated output from thermal generation.

A key driver for the trial has been to develop an understanding how these technologies work and interact in a real-life environment.

The following report is one of a number of related reports undertaken by the University of Strathclyde (UoS). It provides a review of battery energy storage technologies and assesses the operational effectiveness of a 1MW, 3MWh valve regulated lead-acid (VRLA) battery energy storage system (BESS) installed at Lerwick Power Station (LPS) on the Shetland network. Other related reports have covered the knowledge and learning of Demand Side Management (DSM), frequency response, Active Network Management (ANM) system, commercial arrangements and economics, as listed in Figure 1.

NINES Detail Report
DSM: Customer Impact
DSM: Infrastructure
DSM: Network benefits
Battery: Operational Effectiveness
Frequency Response: Customer Impact
Frequency Response: Operational Effectiveness
ANM: Functional Design, Infrastructure & Comms
ANM: Operational Effectiveness
Commercial Arrangements and Economics Report
UoS Knowledge & Learning Report

Figure 1 NINES learning reports.

The grid-scale BESS was integrated with an Active Network Management (ANM) system which was used to manage all components on the SSEN network in an efficient and reliable manner to meet energy demand on the Shetland network while maintaining the system stability subject to a number of specified network constraints. The VRLA BESS at LPS was capable of providing 4MWh of controllable demand to fill demand troughs and to alleviate constraint limits on distributed generation which have non-firm network connections, i.e. ANM Controlled Generation (ACG). Furthermore, a fully charged BESS would inject 3MWh of electricity into the grid with a maximum discharge rate of 1MW to reduce system demands to be met by conventional generation at peak times.

Under the ANM calculated schedules deployed from February to May 2015, the BESS was scheduled as controllable demand to alleviate constraints on ACG, to fill demand troughs and to lop peaks. However, due to operational issues with the ANM calculated schedules which led to an unsatisfactory utilisation of BESS, scheduling was reverted to a manually derived schedule beyond June 2015. The manual schedule aimed to discharge the BESS at peak times and charge it at times of low system demand. Under the up-to-date constraint rules, ACG is limited to the rise of Sullom Voe Terminal (SVT) output above the minimum-take export limit of SVT and constraints on ACG are likely to be most prevalent at times of low demand. If there were constraints to alleviate charging the battery would reduce the ACG curtailment; otherwise, the increase in demand from charging the BESS may increase the efficiency of lightly loaded engine sets at LPS.

Section 2 of this report describes energy storage technology options including the BESS which was utilised on NINES. **Section 3** describes the basic BESS operation and the utilisation under two different schedules, ANM system calculated schedules and manual schedules from September 2014 to August 2015. In **Section 4**, the total project cost and the project replication costs are estimated based on the summarised capital cost and non-energy operating cost of the 1MW, 3MWh BESS; the volume of energy losses that determine the energy-related operating cost is additionally calculated. The impact of the BESS operation on the connection of ACG is analysed in **Section 5**, based on a new real-time algorithm for scheduling the BESS which is also described and evaluated. The impact on conventional generation displaced by the time-shifting of ACG and the cost of using the BESS to alleviate ACG curtailment taking into account the current case and the future case, where a new algorithm will be implemented and the ACG capacity increased to 8.5MW are also described. **Section 6** estimates the savings attributable to conventional generation through the time-shifting of conventional generation and the utilisation of renewable generation enabled by the BESS. In **Section 7** the reactive power support from the BESS is discussed and the conclusions and the contributions to learning outcomes are detailed in **Section 8**.

2

Battery Energy Storage Technology

2. Battery Energy Storage Technology

2.1 Motivation of integrating the BESS

A growing range of energy storage technologies are used for grid support either in distribution or in transmission networks to realise the future low carbon networks. The energy storage technologies fall into five main categories distinguished by the form the energy is stored in. Energy can be stored in electro-chemicals such as batteries, as potential energy such as hydro or compressed air, as electrical energy such as capacitors, or as mechanical energy such as flywheels. Figure 2 provides detailed classifications of energy storage technologies [1].

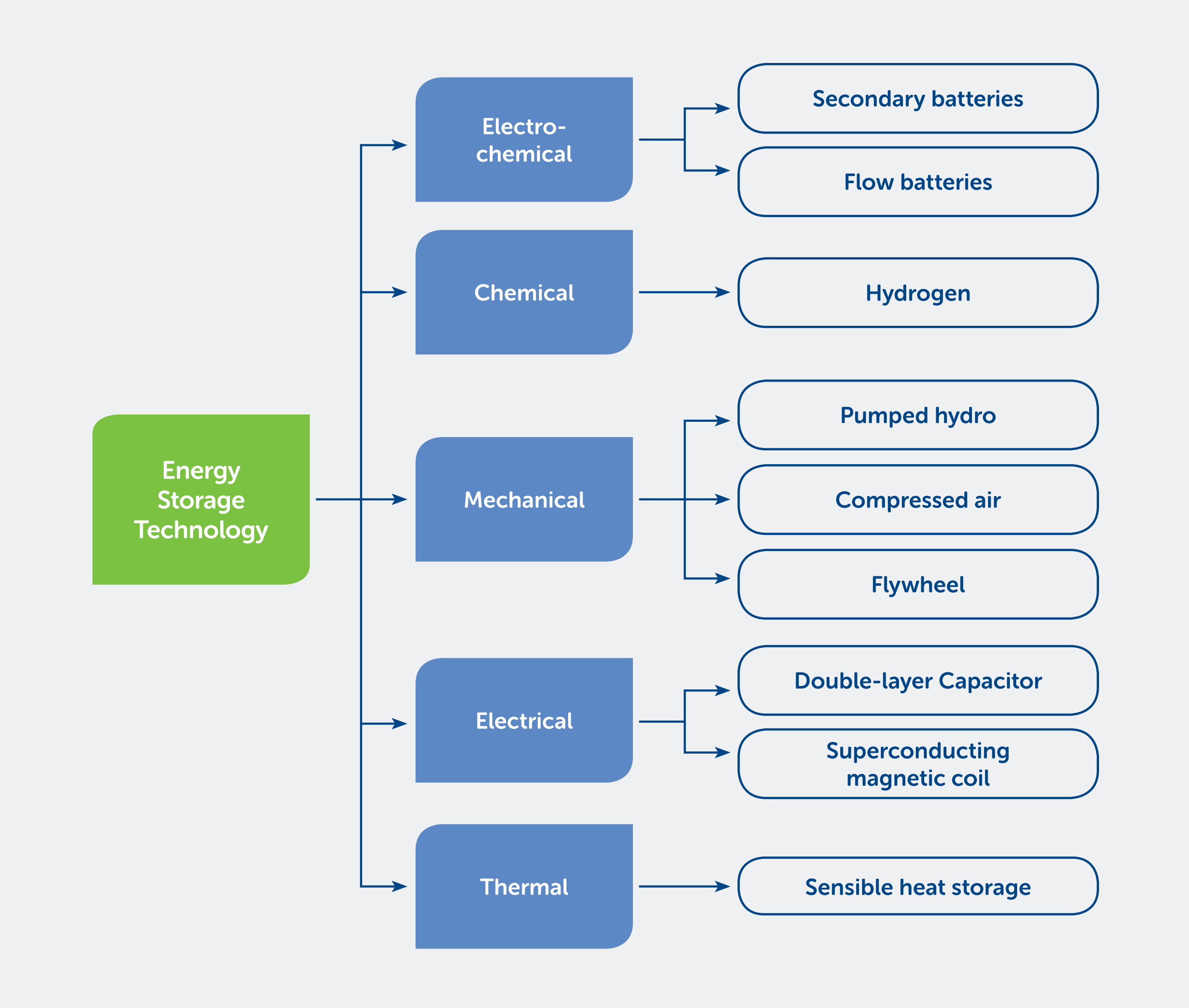

Figure 2 Classifications of energy storage technologies [1].

At grid scale, different energy storage technologies play different roles depending on how often the energy storage system is cycled and the duration of the operation. For example, an energy storage system that operates with a longer discharge or charge duration and fewer cycles per day is usually adopted for the time shifting of conventional generation or renewable generation. For the maintenance of voltage quality, an energy storage system that can supply high power outputs for a short duration with high cycle stability is generally preferred [2].

The technology and scale of the employed energy storage system such as power rating and capacity are mainly determined by the purpose of applying the storage system. Amongst different energy storage technologies, Battery Energy Storage Systems (BESS) currently have the widest range of applications [2] which are manufactured in a wide range of power ratings from less than 10kW to more than 10MW, as shown in Figure 3 [3].

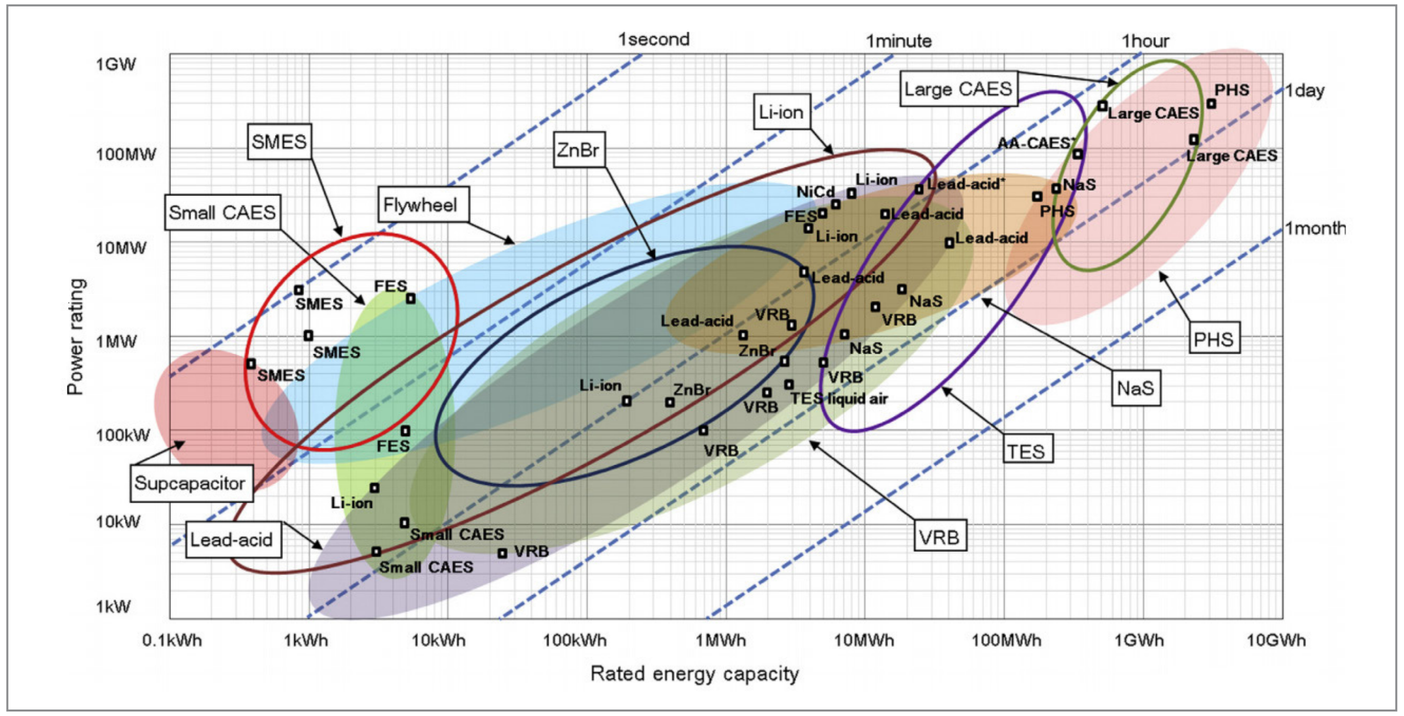

Figure 3 Power ratings and rated energy capacities of different energy storage technologies [3]

One of the most important contributions of BESS is the deferral in reinforcement of electricity networks. It is widely observed that demand is constantly increasing, forcing the network to expand while implementing additional generation, as the current generation cannot cover the growth in demand. BESS can store energy during off-peak times which can then be used in peak demand periods where the generation is not high enough. The concept is that BESS are being charged during periods of generation excess and then discharged during peak times. In addition, if the battery is optimally operated, it may be possible to reduce the maximum demand while allowing new loads to be connected to the network.

Another significant advantage of batteries is that they allow the accommodation of renewable generation [4]. Wind generation is known to cause considerable fluctuations to the system due to variation of wind speed during the day. In addition, wind turbines may produce more power than is needed in a specific period of time requiring the wind farm operators to turn the turbines off. However, a grid-scale BESS could assist in coping with these issues by storing the excess power produced by wind farms during high wind periods and then delivering the power back to the network when wind farms cannot produce energy. In addition, fluctuations can be reduced since the energy stored can be smoothly distributed to the network when the battery discharges.

As was introduced in Section 1, the NINES project aims to reduce the maximum demand and the fossil fuel consumption [5]. A feasible approach to peak shaving and increasing the utilisation of renewables is to integrate the BESS with an Active Network Management system on the network which will be scheduled to discharge during demand peaks and charged at times of low demand or renewable generation congestion. Furthermore, the demand curve of the Shetland network smoothed by the cycles of the BESS could increase the thermal generation efficiency of Lerwick Power Station (LPS), leading to a further reduction in fuel consumption.

2.2 Battery types

The major components in a BESS are batteries, power conversion system (PCS) and devices for connection to the grid. The expected levels of battery voltage and current can be achieved by electrically connecting the battery cells in series and parallel, in which the chemical and electrical energies are converted to each other [6]. Some of the most common battery technologies used in several projects worldwide are sodium sulphur (NAS) battery, Lithium-ion (Li-Ion) battery, lead-acid battery, advanced lead-acid battery and flow batteries, each having its own characteristics [3] which have been introduced in published literature [6], [7].

In August 2011, a 1MW, 6MWh NAS BESS was installed at Lerwick Power Station (LPS) on the Shetland network. However, due to a battery fire which occurred at a NAS installation in Japan two weeks before the commissioning date of the battery, the NAS battery in Shetland had not been involved in the network operation and was removed in May 2013 for safety concerns regarding the location at LPS [8]. The NAS battery has a high energy density (about 218Wh/kg) and a high round-trip efficiency [6]. The operation of the NAS battery, however, has to be kept at a high operating temperature around 350oC [8] by a constant heat input of 46kW to ensure the efficiency and life of battery, which reduces its overall efficiency. For example, the 1MW, 6MWh NAS BESS on the Shetland network was estimated to have an approximate efficiency of 77%.

As a substitute for the NAS battery, the lead-acid battery is a mature, low-cost technology amongst a range of battery technologies but with lower energy density (around 26.6Wh/kg at 0.1C rate) and limited cycle life [9]. Compared with the traditional flooded lead-acid battery, the valve regulated lead-acid (VRLA) battery is closed with a valve, regulated by pressure. Though the VRLA is relatively more costly than a flooded lead-acid battery and has a shorter life, the VRLA has a comparatively higher energy density and requires lower maintenance [9]. In comparison to the originally specified NAS battery, the dimensions of the VRLA are 3 times that of the NAS and the capacity is halved. The specifications of the NAS battery and the currently employed VRLA battery can be found in [8].

2.3 Locations of BESS

A number of criteria such as the particular need and application of the storage technology determine the best location of implementing a grid scale BESS in an electricity network. Theoretically a battery can be installed at any point of the network; however, determining the "ideal" location of the battery mainly depends on the distance between the source that will provide the energy to charge the unit and the loads that will utilise the energy when the unit discharges. Therefore, a battery should be placed in proximity to the source that will charge it in order to minimize the losses to fully charge the unit. In addition, the battery should also be close to the loads that will use its energy.

LPS was selected as a suitable site for the battery as the majority of the load is located at the centre of Shetland close to LPS. Being the first grid scale BESS in the UK, the 24/7 manned operation of LPS provided additional benefits when selecting a site for the system.

3

BESS operation and utilisation

3. BESS operation and utilisation

3.1 BESS Operation

3.1.1 Discharging and charging phases

Following initial tendering and specification exercises with supplier S&C, installation of the original NaS battery was completed in September 2011. However, just prior to the commissioning and energisation of this battery SSEN were informed of a fire in a similar installation in Japan and a decision was taken to remove and replace the NaS battery. The removal was completed in May 2013.

Following this decision SSEN continued to work with S&C Electric (S&C) to identify a suitable replacement battery. Proposals were presented to Ofgem for a replacement option in the form of change requests which were subsequently agreed by Ofgem on 17th September 2013. The replacement 1MW/3MWh lead-acid battery was completed to plan and initially commissioned during February 2014. MW values were recorded at the 11kV circuit breaker and therefore included all incurred energy losses at battery bank, PCS, transformer, etc. In the main, the BESS was scheduled to discharge at peak times and charge during the off-peak. More specifically, the daily discharge was limited to 3MWh in addition to a minimum 45% State of Charge (SOC). Twelve 15-minute discharge periods of 1MW were specified to coincide with peak demands each day.

The BESS was charged at times of low system demand with a higher energy requirement of 4MWh required to recharge the BESS back to its initial SOC due to energy losses during the cycle. The charge rate of the BESS is dependent on the SOC of the battery. An initial charge rate of 1MW reduced to 0.66MW and 0.33MW when the SOC reached 80% and 90% respectively, creating a step down charging profile. Figure 4 shows a complete cycle of the BESS from 07:00 on 03/09/2014 to 07:00 on 04/09/2014 operated under a manual schedule along with the corresponding variation in the SOC of battery. How the total demand to be met by generators varied with the BESS's operation is shown in Figure 5.

It took between 6 – 8 hours to fully charge the BESS as shown in Figure 4 depending on whether an equalisation charge was required. The minimum demands were shown in Figure 5 to occur between 03:00 – 05:00 in the morning at which point the optimum charge rates of the BESS would be 1MW. However, the BESS required approximately seven hours to charge and would not be fully charged before the first peak in the morning. Therefore, the off-peak time of the lowest system demand followed by the morning peak was rarely considered for charging the BESS at a rate of 1MW and a compromise was sought.

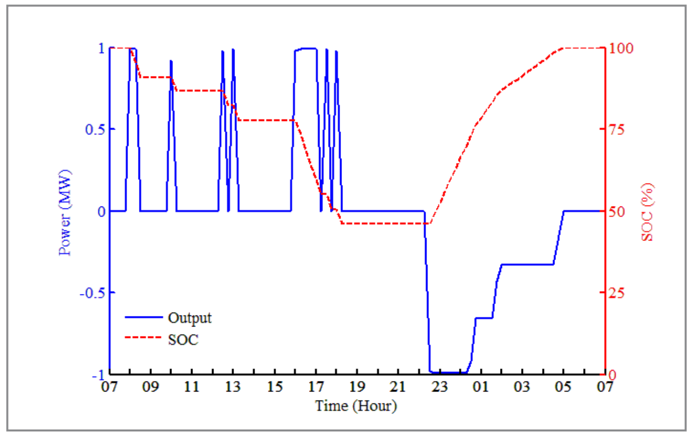

Figure 4 Outputs (MW) of the BESS (discharge rates were positive and charge rates were negative) and corresponding variations in SOC (%) within a complete cycle from 07:00 on 03/09/2014 to 07:00 on 04/09/2014.

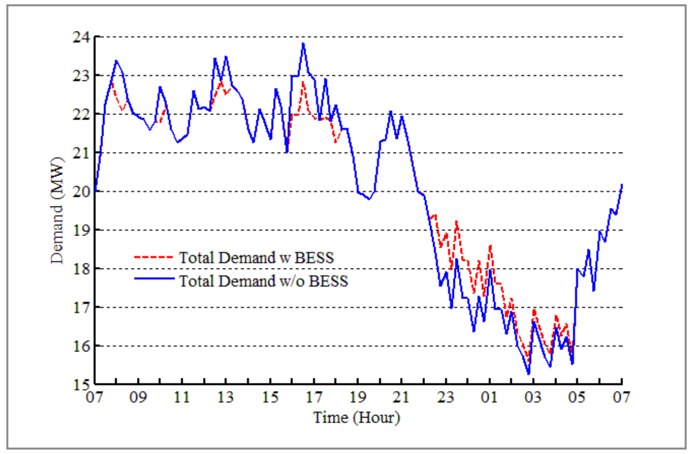

Figure 5 Variations in total demand (MW) to be met by generators following the BESS operation from 07:00 on 03/09/2014 to 07:00 on 04/09/2014

3.1.2 Operational requirements

The percentage of the available energy left in the VRLA battery, i.e. the SOC, must be always greater than or equal to 45% during the discharging phase in order to protect the battery from a harmful deep discharge. During the process of charging, neither overcharging nor undercharging is wanted. A VRLA battery that undergoes excess overcharging faces an increased risk of drying out and premature failure. Undercharging will also lead to a severely shortened life and a significant reduction in the maximum charge capacity, causing the BESS to be over-discharged inadvertently [9]. The Battery Management System (BMS) together with the Power Conversion System contains operational limits specified by the manufacturer to prevent against deep discharge, over charging and limit the rate of charge at higher SOC to ensure that the battery cells are operated within the manufacturer's specification [8]. In addition, voltage and impedance of the batteries are inspected biannually to ensure the battery cells are operating within the limits recommended by the manufacturer [10].

The heat produced within the VRLA battery cells cannot be dissipated effectively since they are not flooded. The temperature of battery cells and ambient temperatures should be carefully monitored and controlled to ensure that the generated heat is effectively dissipated otherwise the battery life will be compromised. The VRLA battery and ambient temperature are recommended in [10] to be maintained at around 25C and 22.2C respectively. (The optimum operating temperature of the VRLA battery at LPS is 20C as stated in [8].) Meanwhile, the difference in temperature among the battery cells should be maintained within ±2.8C. Furthermore, the battery's operating environment must provide sufficient air circulation to eliminate the differences in ambient temperature and the external heat sources, e.g. solar radiation should be avoided [10].

3.1.3 Cycles during the first full year

With a three-hour discharging time and approximately seven-hour charging time there is limited scope to carry out more than one cycle each day. This scope is further reduced due to the timing of the peak loads on the demand curve. Based on the data the BESS completed approximately 288 cycles in the first full year from September 2014 to August 2015. The number of cycles was limited because the BESS was not utilised at weekends during the first period of operation and biannual maintenance was carried out in March and September. Furthermore, a fault with two of the 3168 battery cells led to the battery being removed from the network for a short period of time. The amount of discharged energy per day through its first full year operation is shown in Figure 6 where outages of the BESS which have been referred to are labelled. Given the warranty term is 5 years or 1500 cycles (depends on which comes first), i.e. 300 cycles per annum, 96% of the expected number of cycles was achieved in the first full year and the remaining 12 cycles would be made up in subsequent years.

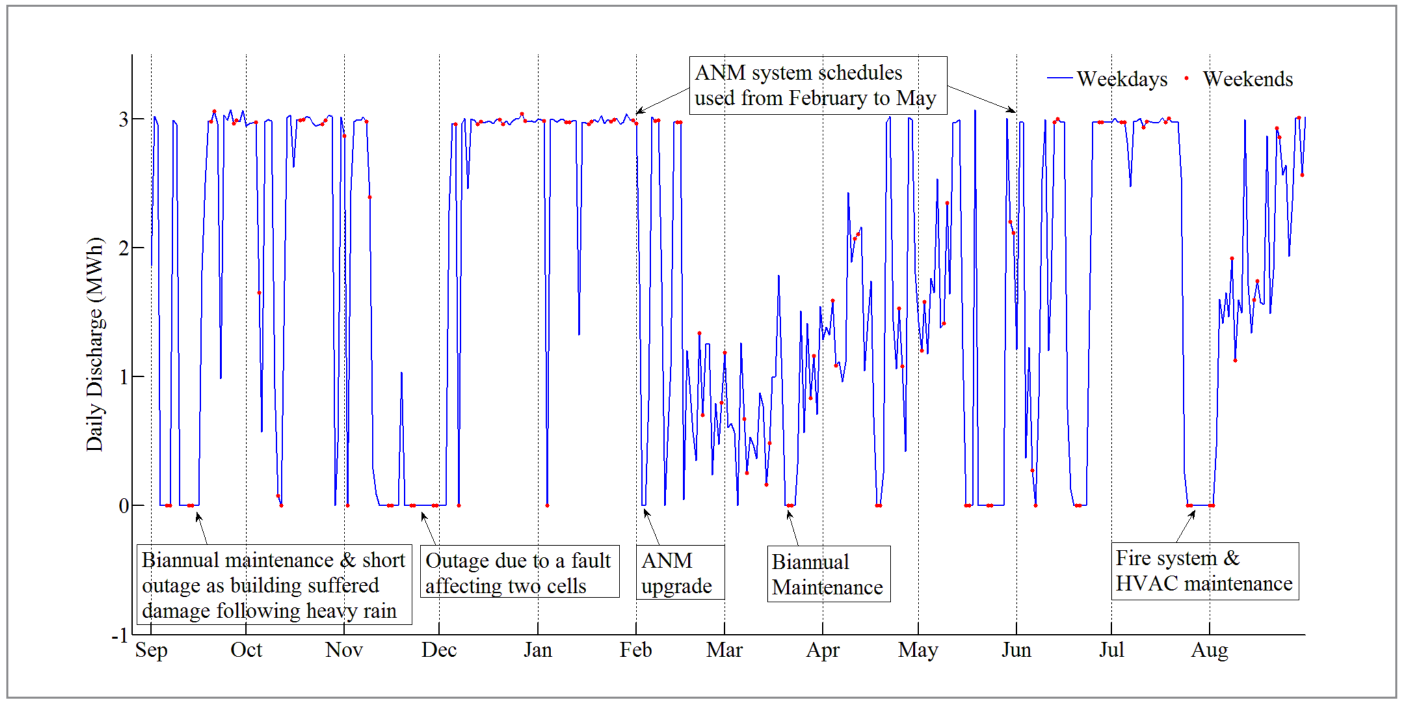

Figure 6 Volumes (MWh) of discharged energy per day in the first full year from September 2014 to August 2015

3.2 BESS Utilisation

3.2.1 ANM system calculated schedule

The devices on the Shetland network inclusive of the BESS and demand side management (DSM) groups were integrated with the ANM system. The BESS was operated under the ANM calculated schedules over four months from February to late May 2015. The objectives were to smooth the demand curve by filling troughs and lopping peaks, and to promote the utilisation of ACG on the Shetland network subject to several constraint rules (CTRs) [11] which were developed by University of Strathclyde (UoS), implemented by Smarter Grid Solutions (SGS) and optimised by SSEN. However, ANM calculated schedules were implemented prior to the optimisation of CTRs. Due to operational issues with initial CTRs charging the BESS would not alleviate ACG curtailment.

Operating the BESS under ANM calculated schedules revealed a number of deficiencies in the ANM algorithm. The schedules did not utilise the 3MWh available from the battery as shown in Figure 6. By not fully discharging the battery, less energy was required to recharge which reduces the controllable demand available to alleviate constraints. Secondly, the algorithm utilised a single energy requirement rather than the two energy requirements expected. This was set to 3MWh therefore the schedule did not provide the 4MWh – or equivalent thereof – necessary to fully charge the battery to 100% SOC [11] and some manual schedule intervention was required to ensure that the battery was fully charged. Based on measurements the BESS completed 98 cycles under the ANM calculated schedules and discharged approximately 138.7MWh in total. Exclusive of the outages made for operational reasons, the utilisation of the BESS was only about 47.2% in this time period.

3.2.2 Manually derived schedule

While the work was on-going to optimise the ANM calculated schedules, the BESS was manually scheduled beyond June 2015. The objective of the manual schedule was to smooth the demand curve through discharging the battery at peak times and charging the battery at times of low demand. As shown in Figure 5, the maximum demand provided by generators was reduced from 23.86MW to 22.86MW by discharging the battery at a rate of 1MW. Furthermore, the standard deviation of total export from generators decreased from 2.5MW to 2.1MW on that day, indicating that the demand curve was largely smoothed.

Based on recorded outputs of BESS, 190 cycles were completed under manual scheduling and 491MWh were injected into the grid in the first full year. When the battery was scheduled to cycle (i.e. excluding the outages) the utilisation of BESS during the periods prior to February 2015 and beyond June 2015 was around 86.1%.

3.2.3 BESS Utilisation in the first full year

Through the first full year operation, the BESS delivered 629.7MWh into the network at peak times and absorbed 826.6MWh from the grid. Given the BESS is expected to complete 300 full cycles and discharge 900MWh per annum the utilisation of the BESS in the first full year was approximately 70%. Figure 7 shows the number of days for different amounts (MWh) of daily discharged energy. It can be seen that, in the first full year, (a) the BESS was not cycled for 77 days; (b) the BESS was largely utilised, i.e. providing greater than 2MWh daily discharged energy accounted for 175 days; (c) there were around 150 days when the volume of daily discharged energy almost reached the expected value of 3MWh; and (d) the battery was not largely utilised (0 – 2MWh) for around 113 days, most of which were due to the ANM calculated schedules as shown in Figure 6.

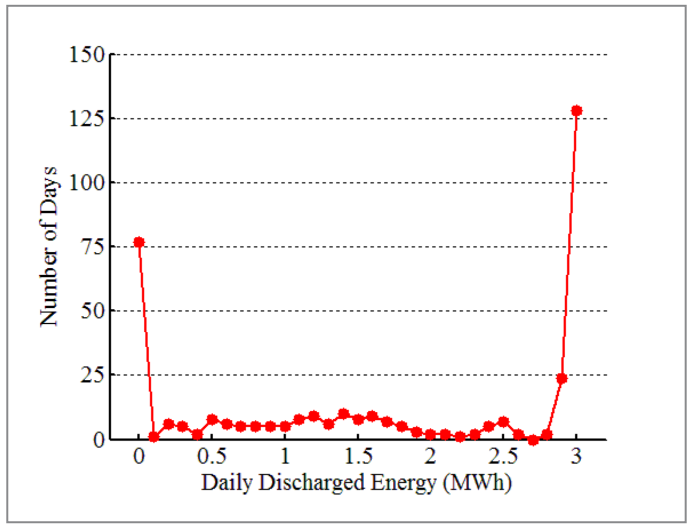

Figure 7 The number of days for different amounts of daily discharged energy

4

Capital and operational expenditure of BESS

4. Capital and operational expenditure of BESS

The costs of the BESS mainly consist of two elements, i.e., the capital expenditure (CAPEX) and the operational expenditure (OPEX). As the one-time cost, CAPEX is the amount of investment that activates the operation of the BESS. The OPEX is a continuous cost supporting the operation of the BESS through its calendar and life cycle [12]. In this section, the CAPEX and the non-energy OPEX of the VRLA BESS on the Shetland network are summarised, from which the total project cost and the project replication cost are approximately estimated. In addition, the volume of energy losses over the period from September 2014 to November 2016 which can be used to calculate the energy-related OPEX based on electricity prices are evaluated.

4.1 Capital Expenditure

Capital expenditure (CAPEX) of an energy storage system generally consists of the investment in the storage unit, power conversion system and other components [13]. The Shetland battery has a number of funding sources including £1,049,060 from the Department of Energy & Climate Change (DECC) [8], £1m from Tier 1 Low Carbon Network Fund, and the remainder coming from the NINES project. As detailed in *NINES Commercial Arrangements Report*, the CAPEX of the VRLA BESS is estimated to be approximately £3,974,000 as listed in Table 1.

4.2 Operational Expenditure

Operational expenditure (OPEX) of the BESS mainly consists of [12]:

(1) the energy-related operating costs (EROC) that are determined by energy losses due to the inefficiency of the BESS;
(2) the non-energy operating costs (NEOC) including:
   a) payments for labour operating the BESS;
   b) costs for maintenance and replacement of components, e.g. battery cells;
   c) the loss-of-life due to equipment wear;
   d) costs for disposing the decommissioned equipment.

Items	Cost	Notes
Battery	£1,550,000	The VRLA battery cost
Auxiliary System, BESS Installation and Commissioning	£1,580,000	Power conversion system, Battery control system, Battery ventilation system, Fire response system, BESS installation & Commissioning
Network Connection	£65,000	
Communication Systems	£20,000	
Civil & Building Works	£700,000	Battery building cost
External Assessment	£59,000	External assessment and validation of the safety case for the battery technologies
TOTAL	**£3,974,000**	

Table 1 The capital expenditure of 1MW, 3MWh VRLA BESS on the Shetland network.

4.2.1 Non-energy operating costs

The warranty provided by the battery's manufacturer covers the maintenance of the unit biannually for 5 years or until the battery reaches 1500 cycles. Therefore, the cost regarding the maintenance of the battery is zero within the warranty. As detailed in *NINES Commercial Arrangements Report*, the costs associated with other non-energy items, i.e. SSEN labour, IT support and battery building maintenance are listed in Table 2. Within the warranty of 5 years or 1500 cycles, the additional non-energy operating cost (NEOC) is approximately £56,500 per annum. It is noted that when the battery reaches 5 years or 1500 cycles, the extendable warranty would be offered with a cost of £18,500 per annum. If it is intended to extend the warranty the total NEOC would be increased to £75,000 per annum.

4.2.2 Energy losses-related operating costs

Provided the BESS was operating at a 100% round-trip efficiency without any energy losses, the energy-related operating cost (EROC) would be zero. However, in reality, the energy losses are unavoidable during both charging and discharging phases, and even when the battery is not cycling (e.g., self-discharging). The non-zero EROC of an operational BESS has to be taken into account for estimating the BESS's OPEX. The EROC for a single time moment can be calculated as the product of the energy loss and the electricity price. Because of the time-varying electricity price, the energy loss at each time step has to be estimated. The total EROC can be determined as the integral of the produce of the electricity price (EP) and the amount of energy losses over time:

$$EROC = \Sigma_{i=1}^{n} 0.25 \text{ x } \{\mathrm{EP}_i \cdot [P_{cha,i}(1 - \eta_{cha})] + \mathrm{EP}_i \cdot [P_{cha,i} \frac{(1-\eta_{dis})}{\eta_{dis})}]\} \quad (1)$$

where,

$i = i^{th}$ time step (15 minutes);
EP_i = electricity price;
$P_{cha,i}$ = charging rate measured at the 11kV circuit breaker;
$P_{dis,i}$ = discharging rate measured at the 11kV circuit breaker;
η_{cha} = charging efficiency;
η_{dis} = discharging efficiency.

Terms $P_{cha,i}$ and $P_{dis,i}$ are the power delivered by or injected into the grid. Therefore, the coefficients in terms of the efficiency used to calculate the energy losses for the charging and discharging phases are in different forms. According to equation (1), the total EROC can be separated into the costs of energy losses in two operating modes, i.e. the charging and discharging phases.

4.2.3 BESS efficiency

4.2.3.1 Round-trip efficiency

It is well known that a BESS requires more energy to charge than it can discharge. This loss or difference between import and export determines the round-trip efficiency of a BESS, also named the cycle efficiency. By definition, the round-trip efficiency of a BESS is the ratio of the discharged energy injected into the grid from the BESS to the energy used to charge it when a discharging/charging cycle is completed between two given levels of state of charge (SOC) [14].

Based on the VRLA BESS's efficiency test carried out at the 11kV circuit breaker where the losses at battery bank, PCS, transformer, etc. were all included in the total energy losses, the round-trip efficiency η_{rt} of the VRLA BESS was determined to be approximately 75% [8]. Therefore, 4MWh of electricity used to charge the BESS will be converted into discharged energy of 3MWh within a complete cycle.

Items	Cost	Notes
Battery maintenance support	£0	Covered by warranty (5 years or 1500 cycles)
Battery building maintenance cost	£1,500	Per annum
SSEN labour	£45,000	Per annum
IT support	£10,000	Per annum
TOTAL	**£56,500**	**PER ANNUM**

Table 2 Non-energy operating costs of 1MW, 3MWh VRLA BESS on the Shetland network within the warranty.

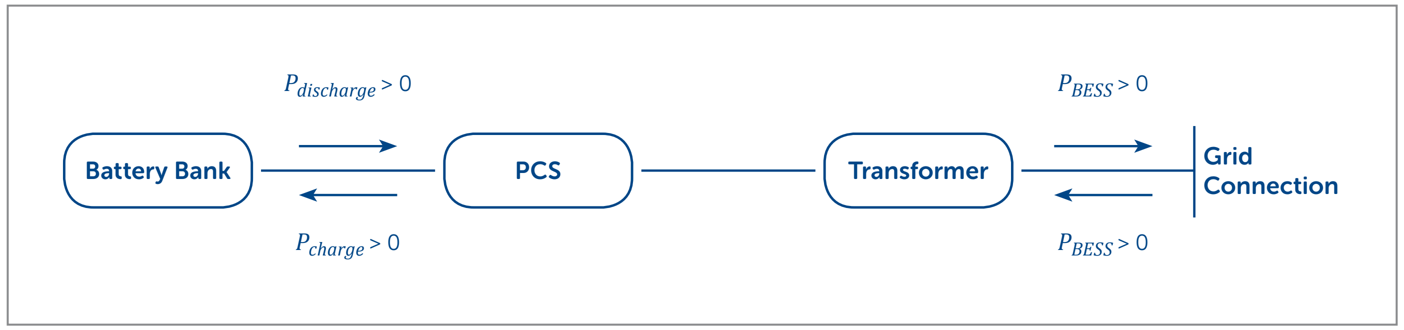

Figure 8 Simplified illustration of a BESS architecture.

The efficiency of the VRLA battery prior to connecting to the PCS was determined to be around 85.5% based on the data measured by a battery management system (BMS) [8]. The battery efficiency in isolation focuses on the battery bank where the largest energy loss occurs rather than the entire energy storage system and is therefore always higher than the round-trip efficiency of the BESS. As shown in Figure 8, the battery efficiency in isolation determined by the integrals of $P_{discharge}$ and P_{charge} over time for a complete cycle ultimately affects the round-trip efficiency of the BESS.

4.2.3.2 Charging and discharging efficiency

The round-trip efficiency η_{rt} of a BESS can be decomposed into a charging efficiency η_{cha} and a discharging efficiency η_{dis} [15]:

$$\eta_{rt} = \eta_{cha} \cdot \eta_{dis} \quad (2)$$

The discharging efficiency is an indicator describing BESS's capability of electricity transmission from the storing state to the discharging state [14]. Though there was no test carried out to examine the discharging or charging efficiency, an approximate estimation of discharging efficiency is made here by assuming that 3MWh electricity injected into the grid from the BESS would reduce the SOC of battery from 100% to the minimum limit of 45%. In other words, the electricity up to 55% of the nominal capacity discharged from the battery bank is decreased to 3MWh injected into the grid due to the energy losses. The VRLA battery consists of 3168 cells, each having a size of 1000Ah specified at the 10-hour discharging rate and a nominal voltage of 2V [8], has a nominal capacity of around 6.336MWh. The discharging efficiency η_{dis} of the BESS is then calculated as:

$$\eta_{dis} \geq \frac{3MWh}{6.336MWh \times 55\%} \times 100\% = 86.1\% \quad (3)$$

The charging efficiency η_{cha} of the BESS is then derived from equation (2) which describes the relationships among terms η_{rt}, η_{dis} and η_{cha}:

$$\eta_{cha} \leq \eta_{rt}/\eta_{dis} = 75\%/86.1\% = 87.1\% \quad (4)$$

4.2.3.3 Impact factors on round-trip efficiency

There are a number of factors that affect the efficiency of the BESS. Battery losses directly affect its round-trip efficiency. Losses are highly dependent on the battery's number of cycles and on the frequency the battery is maintained. Over time, where the battery will have completed a large number of cycles, there will be more energy required to charge the unit and less energy delivered by the unit. The design life has accounted for this and the battery was slightly oversized to ensure that 3MWh of discharged energy was available at the end of battery life. In addition, if the battery was not regularly and properly maintained, it would eventually lead to larger cycles where more energy was required to charge the unit and thus lead to a lower unit efficiency.

The round-trip efficiency of a BESS is also indirectly influenced by some other factors:

1) An excessive charging or discharging rate will generate more heat losses and thus lower efficiency. For example, when the discharging rate increases from the 10-hour discharge rate (0.1C) to the 3-hour discharge rate (0.33C), a battery cell of 1000Ah specified at the 0.1C is expected to deliver 750Ah only. Therefore, it may be feasible to adapt the currents within the limits [8] to improve the battery efficiency [16]. Furthermore, operating at a higher rate will have a negative effect on the battery's cycle life.

2) The operating temperature of a VRLA battery generally ranges from -5°C to 40°C. (The optimum operating temperature stated in [8] is 20°C.) There is a trade-off between the cycle life and the round-trip efficiency since operating at a higher temperature will improve the efficiency but reduce the life of the battery [17].

3) Another impacting factor is the rate of self-discharge which is the capacity dissipation when the battery is left idle. Generally, a VRLA BESS of about 72% - 78% round-trip efficiency has a monthly self-discharge rate of 2% - 5%, while a NAS BESS of around 89% round-trip efficiency has no self-discharge [17] (although the overall efficiency of a NAS BESS may be reduced due to the requirement of a constant heat input.) However, a more efficient BESS usually has a relatively higher CAPEX. A trade-off between the round-trip efficiency and the CAPEX may therefore be additional considered in the selection of battery technology [18].

4.2.4 Calculation of energy losses

Over the period from September 2014 to November 2016, the BESS on the SSEN network in Shetland had absorbed a total of 1.77GWh and discharged 1.34GWh. The difference between import and export of the BESS was equal to 0.43GWh, which was the volume of energy losses over the period of interest. The volume of energy losses can also be estimated in a theoretical way as the product of the coefficient (1-η_{rt}) and the electricity that had been used to charge the BESS which was equal to (1–75%) x 1.77GWh = 0.44GWh. The theoretical estimate of energy losses was slightly higher than the actual volume, revealing that the VRLA BESS was cycling with a satisfactory round-trip efficiency on average, which was greater than an approximate efficiency of 75%.

Based on the estimates of charging and discharging efficiencies in Section 4.2.3.2, the energy losses at each individual charging or discharging time point can be quantified by using P_{cha} (1–η_{cha}) or P_{dis} (1–η_{dis})/η_{dis} respectively. Figure 9 shows the cumulative volume (GWh) of energy losses of the BESS over the period from September 2014 to November 2016. The total volumes of energy losses during charging and discharging phases were estimated to be around 0.216GWh and 0.228GWh respectively. The OPEX related to the EROC can be calculated when the time-varying electricity price is known.

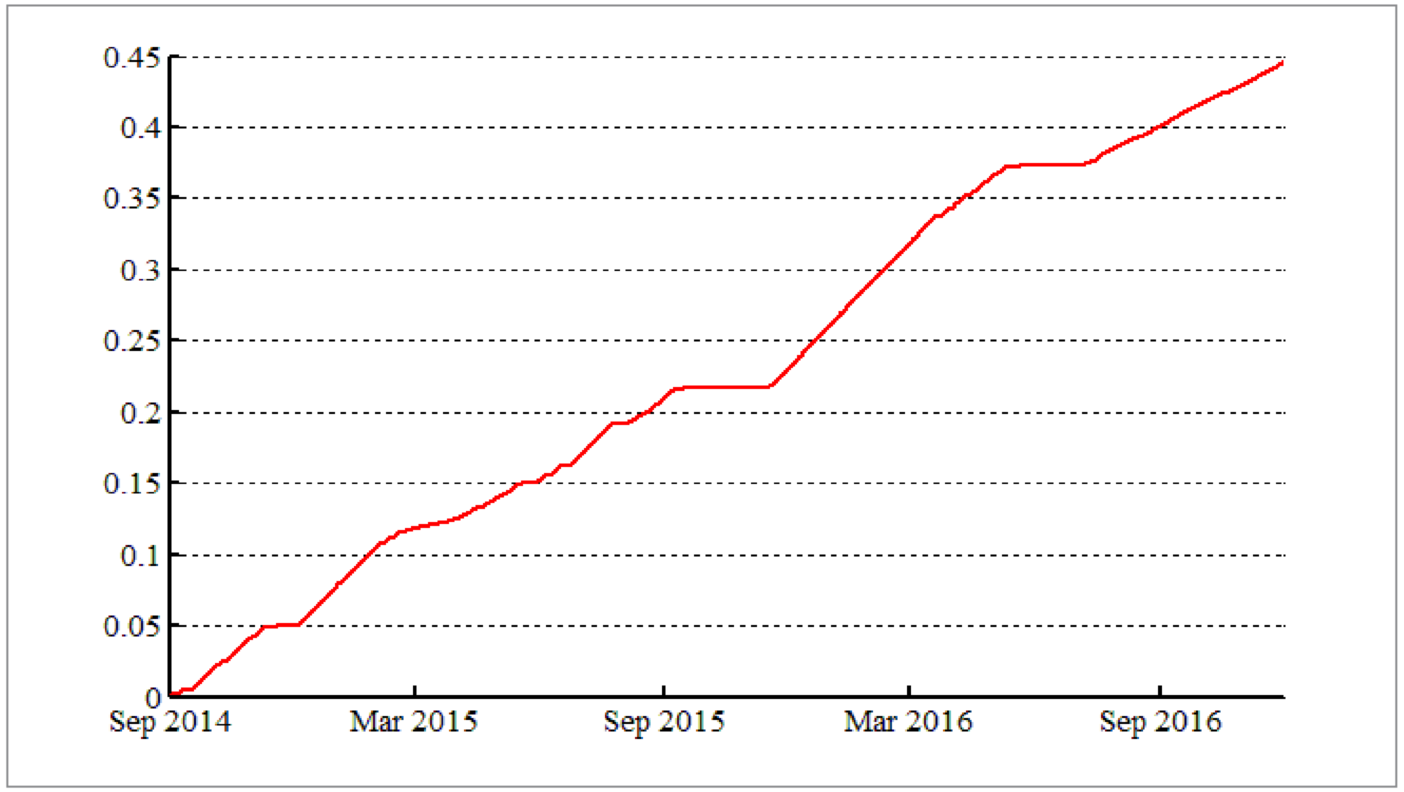

Figure 9 Cumulative volume (GWh) of energy losses of the BESS from September 2014 to November 2016.

4.3 Total Costs and Replication Costs of Project

It has been two and a half years since regular operation of the BESS commenced in September 2014. The total project cost is approximately estimated as a sum of the capital cost and the non-energy operating cost (NEOC) for 2.5 years, i.e. £3,974,000+£56,500×2.5=£4,115,250. Based on the capital cost and the NEOC evaluated in Sections 4.1 and Section 4.2.1, the project replication costs within 15 years are calculated as shown in Figure 10. A timeframe of 15 years is selected here assuming that the VRLA battery has a lifetime of 15 years based on the chronological life summarised by EA Technology [7], where the life of the lead-acid battery is between 5 and 20 years. There is a £56,500 growth in the replication costs per annum within the first five years as the maintenance cost is covered by the warranty (assuming the battery completes 300 cycles per annum). Since the sixth year, the annual growth in the replication costs is £75,000 due to an addition of the extensible warranty which requires £18,500 per annum. The project replication cost would reach £5,006,500 at the end of the 15th year.

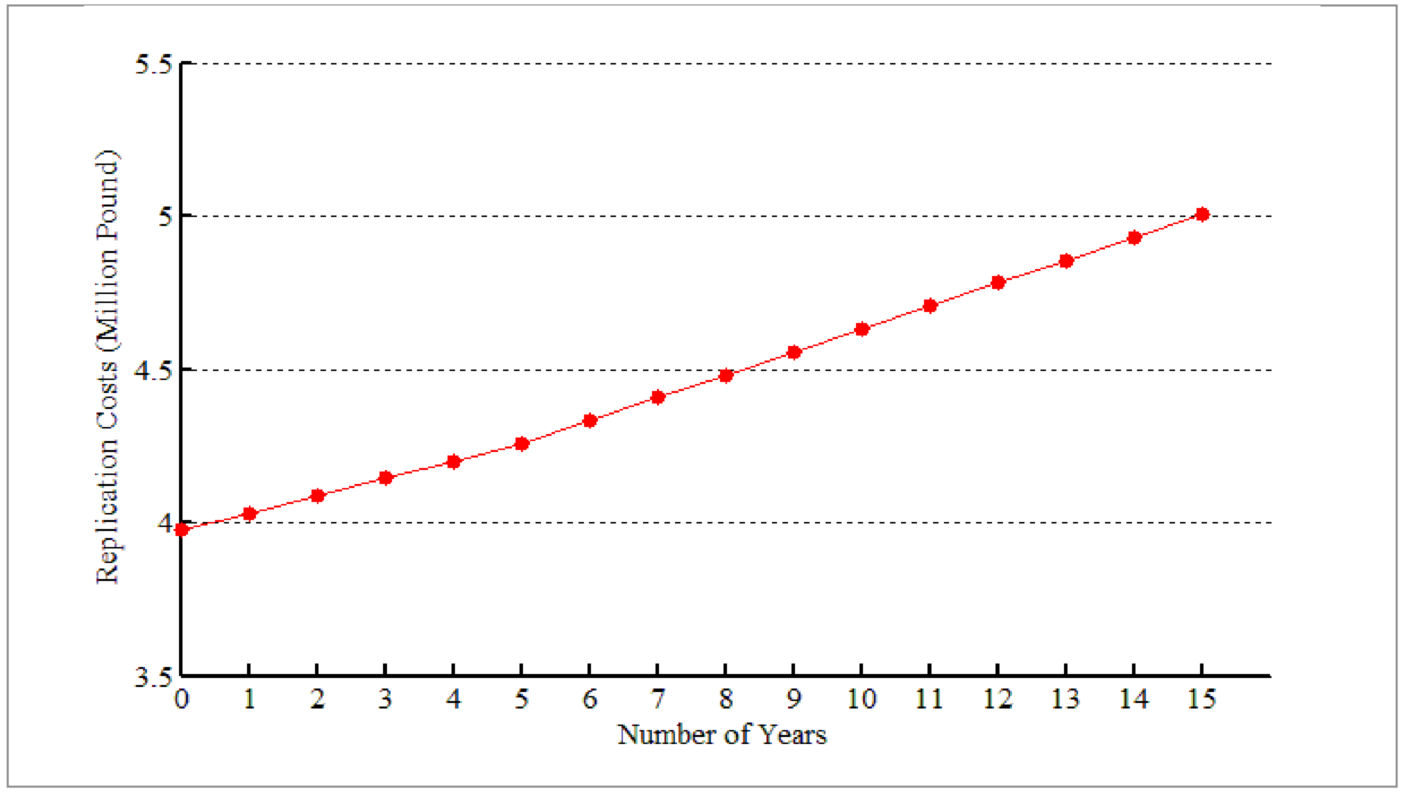

Figure 10 The project replication costs (£m) in 15 years.

5

Impact of BESS Operation on Connection of ANM Controlled Generation

5. Impact of BESS Operation on Connection of ANM Controlled Generation

There are various sources of renewable energy in Shetland. In addition to three main generation sources, i.e., LPS, SVT and Burradale wind farm, the Shetland network is supported by non-firm distributed generation at North Hoo (0.5MW), Luggies Knowe (3MW), Tidal Array (0.5MW) and Garth (4.5MW) under flexible contracts which were commissioned in November 2014, December 2015, December 2015 and March 2017 respectively.

The non-firm distributed generation, i.e. ANM Controlled Generation (ACG) was also integrated with the ANM system. The functional ANM system consisting of SGS Balance and SGS Power Flow, as detailed in ANM Functional Design, Infrastructure & Comms, was commissioned in February 2015 prior to which North Hoo was operated via a fixed set-point of 0.5MW. SGS Balance would utilise wind forecast data to determine profiles for ACG. Controllable demand was then scheduled to alleviate constraints identified in the scheduling process. SGS Power Flow monitors the CTRs and ACG output in real-time to determine set points for ACG.

5.1 Constraint Rules in SGS Balance and SGS Power Flow

SGS Balance and SGS Power Flow use the same set of constraint rules (CTRs) with inputs derived from forecasts or real-time data respectively. The CTRs were developed by UoS, implemented by SGS and optimised by SSEN with an aim to maintain the stability of the Shetland network. The initial rules monitor: SVT status (CTR0), frequency stability (CTR1), spinning reserve (CTR2), and network operation (CTR3):

$$\text{CTR0} = \begin{cases} 0 \text{ SVT Offline} \\ 1 \text{ SVT Online} \end{cases} \quad (5)$$

$$\text{CTR1} = 14.3 - \text{P (BUR)} - \text{Margin1} \quad (6)$$

$$\text{CTR2} = 20 - \text{P(SVT)} - \text{P(BUR)} - \text{Margin2} \quad (7)$$

$$\text{CTR3} = 0.6 \times (\text{Total Demand}) - \text{P(SVT)} - \text{P(BUR)} - \text{Margin3} \quad (8)$$

where *Total Demand* is calculated to be the sum of power output P(·) of all generating plant on the network. The configurable margins were initially set to one. The fast-acting SVT can accommodate high renewable output and provide both primary and secondary frequency response following loss of all renewable generation on Shetland. When SVT is off-line, i.e. CTR0=0, all ACG export is to be curtailed to ensure the stability of the Shetland network. The key criteria for frequency stability is that the Shetland system frequency can be maintained within +/- 2% of nominal (+/- 1Hz). Based on dynamic simulation of the Shetland system under the worst-case frequency deviations following instantaneous loss of all renewable generators, the instantaneous ACG export (i.e. CTR1), in combination with the instantaneous export from Burradale, must not exceed 14.3MW. In addition, the sum of the instantaneous exports from ACG (i.e. CTR2) and Burradale must be maintained within the constraint of spinning reserve which equals the difference between 20MW and the instantaneous SVT export. This ensures that sufficient spinning reserve is provided by the fast-acting SVT generators to meet system demand following an instantaneous outage of all renewable generation on Shetland. The network operation constraint was formulated based on the requirement that LPS should supply at least 40% of the system load. Therefore, the total exports from ACG (i.e. CTR3), SVT and Burradale must not exceed 60% of the total system demand. Due to operational issues experienced with both CTR2 and CTR3 they have been negated through the use of negative margins and an additional constraint rule CTR4 was introduced beyond September 2015, ensuring that the SVT output was greater than the minimum-take export limit:

$$\text{CTR4} = \text{P(SVT)} + \text{P(ACG)} - \text{P(SVTc)} - \text{Margin4} \quad (9)$$

where the minimum-take export limit of SVT is denoted by P(SVTc) and Margin4 is currently equal to zero. The limit on ACG export is usually determined by a Binding Constraint (BC) which is made up of these CTRs:

$$\text{BC} = \text{CTR0}\times\min(\text{CTR1, CTR2, CTR3, CTR4}) \quad (10)$$

The Binding Constraint is currently dominated by CTR4 due to the fact that the minimum value of CTR1 is always greater than the total capacity of connected ACG, and CTR2 and CTR3 have been negated by negative margins. As an illustration, Figure 11 shows the values of CTR3 over a day from 07:00 on 31/05/2016 to 07:00 on 01/06/2016 during which negative margins of -13 and -10 were used to negate CTR2 and CTR3 respectively, and CTR4 determined the Binding Constraint.

In practice, the fast-acting governors at SVT 'grab' or release the load to accommodate the ACG export. Without CTR4, the fast-acting governors at SVT would reduce output. As SVT output reduces the calculated ACG limit from CTR2 and CTR3 increases. The increasing ACG output would first breach the minimum-take export limit of SVT. Left unchecked and with enough ACG available the reverse power flow protection at SVT would then be triggered and lead to CTR0=0, i.e. BC=0, which curtails all ACG export. It is likely an unacceptable under frequency event would follow. The implementation of CTR4 has therefore been critical to preventing the operation of reverse power flow protection at SVT and operating the network securely.

5.2 Impact of BESS Operation on ACG connection

When the additional rule CTR4 was deployed along with the negation of CTR2 and CTR3, the 1MW growth in system load from charging the battery would be grabbed by the fast-acting SVT export, leading to a 1MW increase in the SVT export. According to equation (9), CTR4 would then be increased by 1MW which provides an additional 1MW of headroom for ACG to generate. If the ACG was curtailed at this moment, the fast-acting SVT would release the load up to 1MW to allow additional ACG to be put onto the network, therefore reducing ACG curtailment.

As analysed above, the 1MW growth in total generation output (TGO) from charging the battery would lead to 1MW increase in the limit on ACG export when CTR4 was implemented on 01/09/2015. Therefore, charging the battery could provide additional headroom for ACG to generate and thus may allow additional ACG on the network which would otherwise be curtailed if the battery had not been charged. Though the operation of BESS under the manual schedule was not optimised to reduce the curtailment of ACG, the charging phase of the battery that coincided with high ACG curtailment might have increased the ACG limits and thus indirectly benefited ACG. But it is noted that during the discharging

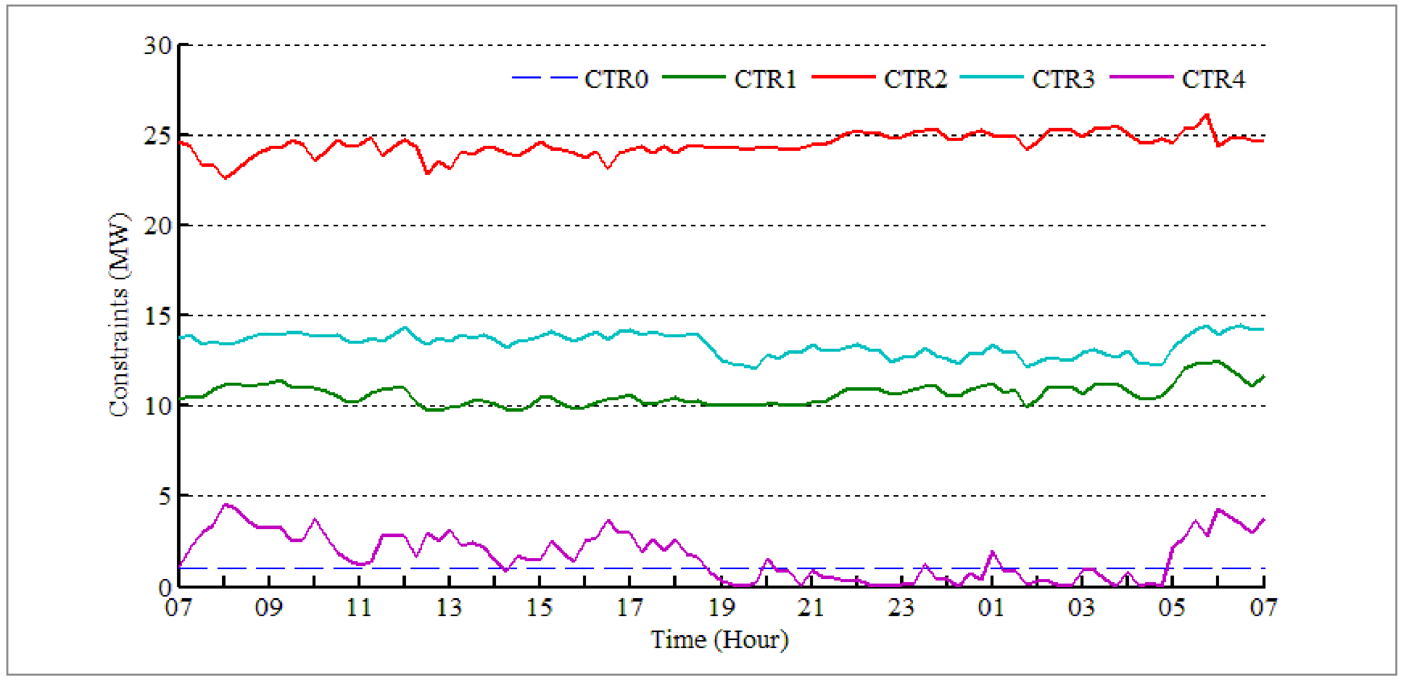

Figure 11 Values (MW) of constraint rules (CTRs) from 07:00 on 31/05/2016 to 07:00 on 01/06/2016.

phase, the 1MW discharge would have the potential to let SVT release the 1MW of load and then lower the ACG limit by 1MW. Fortunately, the ACG limits at peak times were usually higher than the ACG export and the 1MW reduction in the ACG limit would not curtail the ACG export.

As an illustration, four particular cases are shown in Figure 12 in which the ACG limits at the charging times are denoted by 'Limit w BESS' and the ACG limits if the BESS had not been charged are denoted by 'Limit w/o BESS'. The outputs of each generating plant and the calculated values of Limit w BESS and Limit w/o BESS are listed in Table 3.

Case (a): charging the BESS reduced the ACG limit at 01:15 on 31/08/2015 prior to the implementation of CTR4;

Case (b): the Knowe (LK) export was not curtailed and the increase in ACG limit avoided the curtailment of North Hoo (NH) only at 22:15 on 21/01/2016;

Case (c): the increase in ACG limit avoided the curtailment of both LK and NH at 22:00 on 14/01/2016;

Case (d): the ACG would not be curtailed even if the battery had not been charged at 21:30 on 31/03/2016.

Case	LPS	SVT	SVTc	BUR	LK	NH	BESS	Limit w/o BESS	Limit w BESS
(a)	8.77	7.95	N/A	1.2	N/A	0.21	-0.98	1.12	0.73
(b)	20.66	5.68	5	3.68	2.93	0.47	-0.99	3.09	4.08
(c)	19.77	5.35	5	2.99	2.2	0.24	-0.98	1.81	2.79
(d)	14.38	5.52	5	3.44	1.92	0.30	-0.32	2.42	2.74

Table 3 Outputs (MW) of each generating plant and values (MW) of Limit w BESS and Limit w/o BESS in four cases.

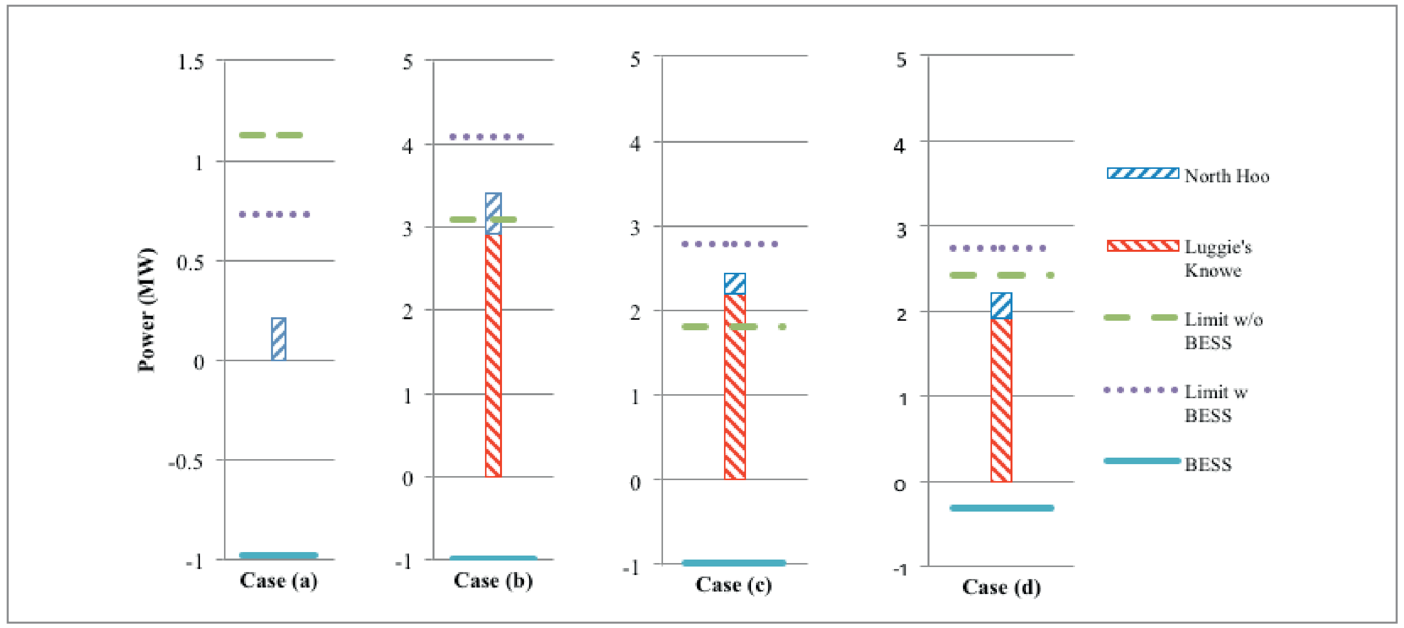

Figure 12 The influence of charging the BESS on the ACG limit.

In case (a) where CTR3 determined the ACG limit, the 0.98MW growth in TGO from charging the battery increased the SVT export from 6.97MW to 7.95MW. The ACG limit without the battery being charged Limit w/o BESS was equal to (0.6×17.15-6.97-1.2-1)=1.12MW. The limit was reduced to Limit w BESS equal to (0.6×18.13-7.95-1.2-1)=0.73MW when the BESS was charged at 0.98MW. Charging the battery would reduce the ACG limit and therefore would not alleviate ACG curtailment prior to the implementation of CTR4.

In case (b) where the ACG limit was determined by the CTR4, the export of LK was not curtailed but 0.31MW of NH power would be curtailed if the battery had not been charged. Charging the BESS at a rate of 0.99MW increased the limit on ACG by the same volume. The 0.31MW curtailment at NH was then avoided.

In case (c) where the CTR4 dominated the ACG limit, the headroom for ACG to generate was only 1.81MW if the BESS had not been charged, which resulted in that 0.39MW available power at LK and all the 0.24MW available power at NH had to be curtailed. Through charging the BESS at 0.98MW which increased the ACG limit from 1.81MW to 2.79MW, the curtailment at LK and NH were both avoided.

In case (d) the limit on ACG export determined by CTR4 would be 2.42MW if the battery had not been charged, under which the ACG with a total export of 2.22MW was not curtailed. Though the ACG limit was increased to 2.74MW by charging the battery there would be no additional ACG export to be put onto the network.

5.3 New real-time algorithm

A new real-time algorithm has been developed by SSEN under the existing control architecture. One of the objectives is to charge the battery in direct response to ACG being curtailed. As CTR4 is the dominant rule that determines the constraint on ACG export, charging the BESS will increase the ACG limit by the same volume as the charge rate. Therefore, the charge rate of the BESS determined by the real-time algorithm is equal to the lower value of ACG curtailment and the maximum limit on the charge rate that is dependent on the SOC of battery:

$$P_{cha,i} = \min\{ACG_{curtail}, P_{cha}^{max}(SOC)\} \qquad (11)$$

$$P_{cha}^{max}(SOC) = \begin{cases} 1MW & 45\% \le SOC < 80\% \\ 0.66MW & 80\% \le SOC < 90\% \\ 0.33MW & 90\% \le SOC < 100\% \end{cases} \qquad (12)$$

How the real-time algorithm determines the BESS's charging phase is illustrated here using the data over the period from 21:00 on 31/05/2016 to 05:00 on 01/06/2016 during which time the BESS was not charged. The available powers of NH and LK were assumed to be proportional to the recorded outputs of the 3.68MW Burradale wind farm which has a firm network connection. The set of constraint rules (CTRs) within this period has been estimated as shown in Figure 11 where the constraints on ACG export were dominated by CTR4. Figure 13 compares the total available power of ACG with the corresponding limits on ACG export. It is shown that the ACG had to be curtailed for most of the time, except for the time points of 01:00 and 05:00 on 01/06/2016.

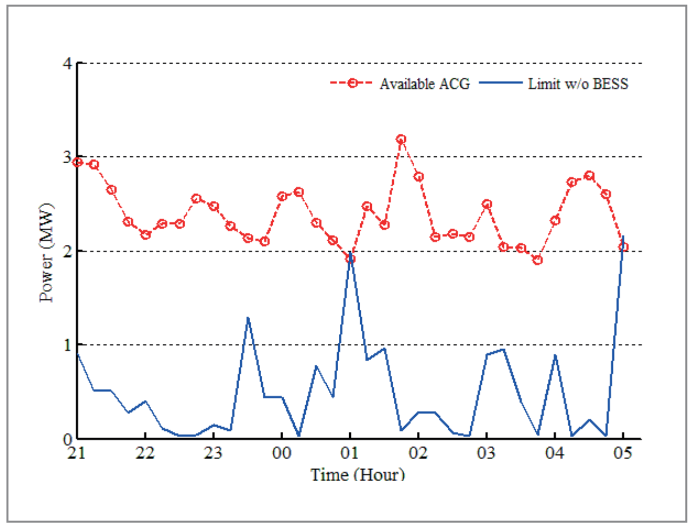

Figure 13 Available powers of ACG and limits on ACG export over the period from 21:00 on 31/05/2016 to 05:00 on 01/06/2016.

Under the real-time algorithm, the BESS would be charged at the times ACG was being curtailed subject to the maximum allowable charge rates. Assuming that 4MWh of electricity was required to charge the BESS to 100% SOC, the charging times and the corresponding charge rates would be determined according to equations (11) and (12). Figure 14 shows the charge rates of the BESS determined by the real-time algorithm and the corresponding variations in the SOC of battery.

The curtailment of ACG export was equal to 0.84MW at 23:30 on 31/05 as shown in Figure 13 where the maximum allowable charge rate was 1MW as the SOC was less than 80% as shown in Figure 14. Charging the BESS at 0.84MW would increase the constraint on ACG export by 0.84MW, thus avoiding the ACG curtailment. When it came to 01:00 on 01/06, ACG was not curtailed as shown in Figure 13 and therefore, the BESS would not be charged. The charge rates at other time points reached the maximum values determined by the SOC as the volumes of ACG curtailment was greater than the SOC-dependent maximum allowable charge rates.

Under the real-time algorithm, all the energy used to charge the BESS would be supplied by the ACG export which would otherwise be curtailed. Based on the evaluation carried out here, the implementation of the new real-time algorithm which primarily aims to charge the battery in response to the ACG curtailment may promote the utilisation of renewable generation in an efficient way.

The 3.5MW ACG was not curtailed at times when the system demand was still at a high level during the off-peak times. This led to high SVT export and therefore the limits on ACG export were greater than the ACG capacity. For example, the SVT export was as least 5MW greater than the minimum-take export limit of SVT over the period from 21:00 on 03/11/2016 to 05:00 on 04/11/2016. In this period, the additional energy used to charge the battery would be from conventional generation as the ACG export was still less than the limits if the battery had

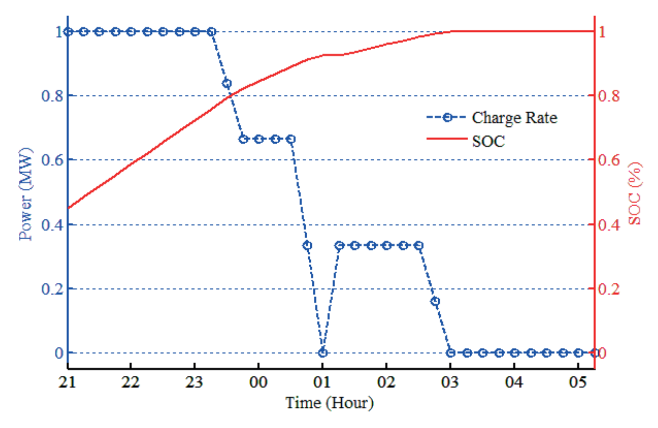

Figure 14 Charge rates (MW) determined by the real-time algorithm and the corresponding variations in SOC (%) over the period from 21:00 on 31/05/2016 to 05:00 on 01/06/2016.

not been charged, as shown in Figure 15. If this case or similar cases occur, the real-time algorithm may not work to charge the battery when it is implemented to schedule the BESS. Fortunately, the maximum capacity of ACG on the Shetland network has now reached 8.5MW under NINES. The large increase in the total installed capacity of ACG will preserve the advantage of the real-time algorithm in reducing ACG curtailment at almost all times of the year.

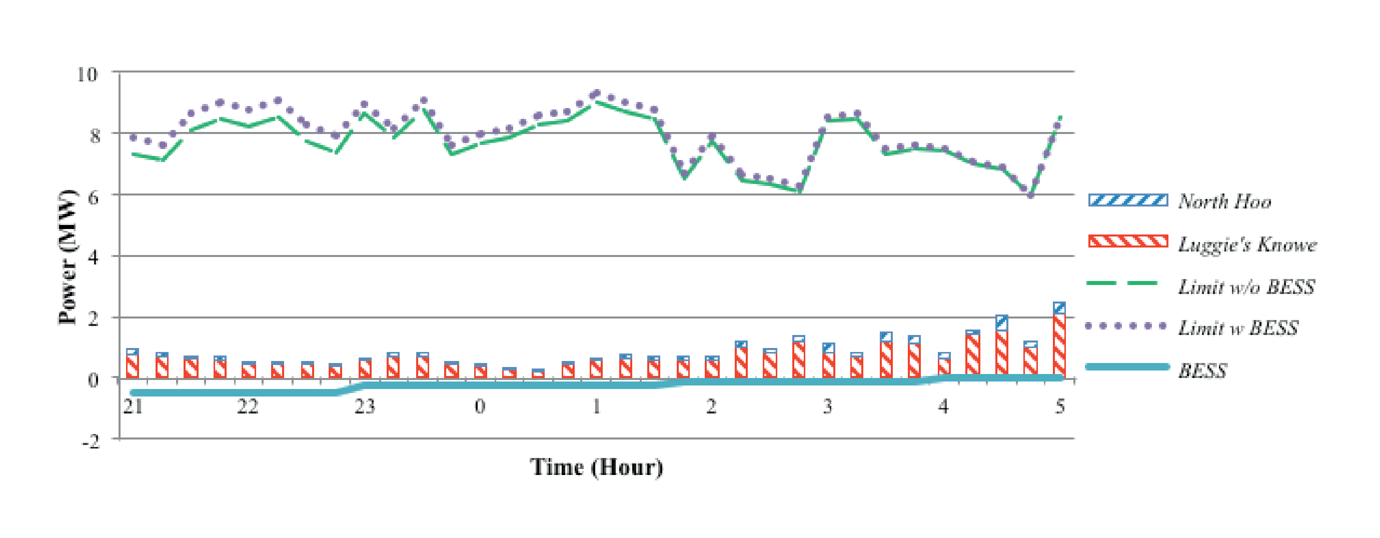

Figure 15 ACG export, Limit w/o BESS and Limit w BESS from 21:00 on 03/11/2016 to 05:00 on 04/11/2016.

5.4 Indirect benefits of additional ACG export enabled by BESS

As discussed in Section 5.2, alleviating constraints on ACG from charging the BESS might have provided additional headroom for ACG to generate which would otherwise be curtailed if the battery had not been charged. The energy stored in the BESS provided by additional ACG was then injected into the grid at peak times with a rate of 75% round-trip efficiency, which reduced the demands to be met by conventional generation and corresponding conventional generation costs.

5.4.1 Volume of additional ACG export

The ACG export was limited by different representations of constraint rules over the period from February 2015 to November 2016. Prior to the implementation of CTR4 on September 2015, charging the battery reduced the ACG limit and therefore would not alleviate ACG curtailment due to operational issues with CTR2 and CTR3. When CTR4 was implemented on 01/09/2016, the increase in the limit of ACG export from charging the battery enabled ACG to put additional energy onto the network which would otherwise be curtailed. In the period under review this totalled 597.25 hours. The volumes of additional export of NH and LK absorbed by the battery were calculated through comparing the outputs of NH and LK with the limit on ACG export ('Limit w BESS') and the limits if the battery had not been charged ('Limit w/o BESS'). Figure 12 has shown four examples in which the volumes of additional ACG were 0MWh, 0.08MWh, 0.16MWh and 0MWh respectively.

Another example is shown in Figure 16 where the ACG export (i.e., the sum of export of NH and LK) were compared with Limit w/o BESS and Limit w BESS over a consecutive time points from 21:00 on 31/03/2016 to 05:00 on 01/04/2016, during which around 3.9MWh electricity was used to charge the BESS. Over this period, charging the battery at off-peak times had allowed NH and LK to additionally generate 0.15MWh and 0.66MWh which would otherwise be curtailed.

The volumes of additional export of NH and LK enabled by charging the BESS were estimated to be about 18.1MWh and 34.6MWh respectively over the period from September 2015 to November 2016. Compared with the amount of energy used to charge the battery (0.94 GWh from September 2015 to November 2016), the volume of additional ACG export enabled by the battery which would otherwise be curtailed was relatively small. This was in part due to only 0.5MW ACG connected to the network until February 2016 when LK was fully commissioned. The 0.5MW ACG was rarely curtailed which affected the battery's ability to reduce the ACG curtailment for most of the operational period. Furthermore, the battery was not directly scheduled to alleviate the real-time constraints on ACG. Section 5.3 has described a new real-time algorithm which has been developed by SSEN to charge the battery in direct response to the ACG curtailment and will be included

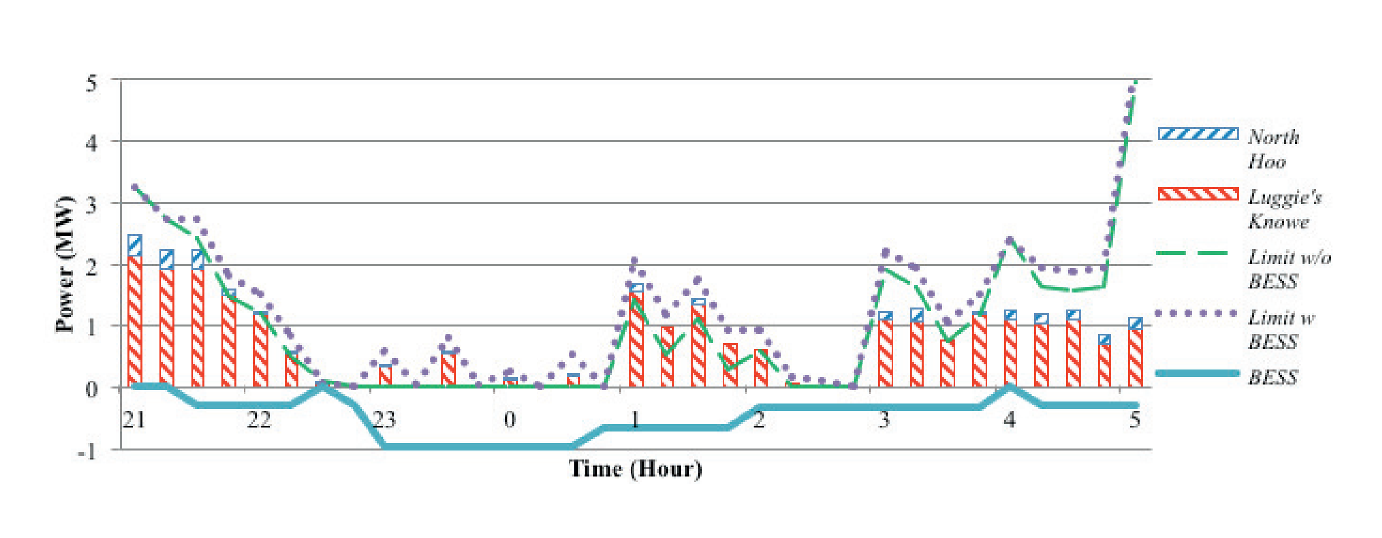

Figure 16 ACG export, Limit w/o BESS and Limit w BESS from 21:00 on 31/03/2016 to 05:00 on 01/04/2016.

in an upgraded ANM platform in 2017. With the real-time algorithm and the increase in ACG capacity to 8.5MW, the battery's capacity would be largely utilised to alleviate the ACG curtailment.

5.4.2 Cost of additional ACG export

The cost of putting additional ACG onto the network primarily consists of feed-in tariffs (FITs). The FITs are made up of two components, i.e., (a) the 'generation tariff' which is a fixed price (p/kWh) dependent on the technology type and installation size; and (b) the 'export tariff' that is a bonus payment (p/kWh) of surplus electricity exported to the network [19]. The payment will be made to distributed generators and paid by licensed electricity suppliers. The ACG has the opportunity to decline the export tariff and try to negotiate its own power purchase agreements (PPAs) with electricity suppliers. In this section, the export tariff is used to provide a reasonable estimate.

The values of the generation tariff and the export tariff for 0.5MW North Hoo, 3MW Luggies Knowe and 4.5MW Garth wind farms that are adjusted by the annual Retail Price Index are listed in Table 4 and Table 5.

Based on the volumes of additional export of NH and LK calculated in Section 5.4.1, combined with their generation and export payment rates listed in Table 4 and Table 5, the payment of FITs made to the NH and LK wind farms for their additional export were approximately estimated to be £4325.47 and £2785.24 respectively. The calculations of the FIT payments are detailed in Table 6.

Sizes (MW)	Registration Date	Generation Payment Rate (p/kWh)	
		Year 15/16 [20]	Year 16/17 [21]
0.5	November 2013	18.83	19.06
3	December 2014	3.12	3.16
4.5	September 2015	2.77	2.80

Table 4 Generation payment rates (p/kWh) for 0.5MW North Hoo, 3MW Luggies Knowe and 4.5MW Garth wind farms.

Sizes (MW)	Registration Date	Export Payment Rate (p/kWh)	
		Year 15/16 [20]	Year 16/17 [21]
0.5	November 2013	4.85	4.91
3	December 2014	4.85	4.91
4.5	September 2015	4.85	4.91

Table 5 Export payment rates (p/kWh) for North Hoo, Luggies Knowe and Garth wind farms.

Wind Farm	Year	Additional Export (MWh)	Generation Payment (£)	Export Payment (£)	TOTAL PAYMENT (£)
North Hoo	15/16	5.35	1007.41	259.48	**4325.47**
	16/17	12.76	2432.06	626.52	
Knowe	15/16	5.36	167.23	259.96	**2785.24**
	16/17	29.22	923.35	1434.70	

Table 6 FIT payments (£) for additional export enabled by BESS.

5.4.3 Generation displaced by additional ACG

The additional ACG export was absorbed by the BESS and then injected into the grid at peak times. Over the period from September 2015 to November 2016, additional ACG of 52.7MWh directly used to charge the BESS was converted into 39.5MWh (i.e. 75% x 52.7MWh) of electricity delivered to the grid due to the energy losses within the BESS's operation. An estimated cost for conventional generation in Shetland in the period evaluated is £200/MWh which includes all usage, spinning reserve, fuel and maintenance. The cost of conventional generation displaced by additional ACG at peak times was therefore estimated to be £7905 (i.e. £200/MWh x 39.5MWh), which was £794.29 higher than the total FIT payment for the additional ACG. Considering the electricity suppliers apportion the FIT costs to all their electricity customers, only the export rate is part of the Shetland costs. Therefore, the fees paid to North Hoo and Luggies Knowe for their additional energy exported to the grid through PPAs were estimated to be approximately £886 and £1694.66, totalling £2580.66. The time-shifting of renewable generation enabled by the BESS saved £5324.34 through delivering the absorbed ACG to the grid at peak times.

The real-time algorithm has been evaluated here to schedule the battery to absorb the surplus ACG export which would otherwise be curtailed. Therefore, under the schedules derived from the real-time algorithm, 4MWh of ACG would be absorbed by the BESS and converted into 3MWh that is injected into the grid at peak times in a full charge/discharge cycle. Following the 4.5MW Garth wind farm's commissioning the total capacity of ACG on the Shetland network has now reached 8.5MW. North Hoo is likely to be highly constrained and diverts power for internal use as the majority of access to the network is taken up by Garth followed by Knowe. (North Hoo is often seen to divert power for internal use despite receiving a full set-point from the ANM system.) In other words, the energy used to charge the battery is mainly from Garth and Luggies Knowe. The cost of 4MWh charged energy supplied by Garth and Luggies Knowe is therefore estimated to be approximately £300 based on an approximate average rate for Garth and Knowe, i.e. £75/MWh. The cost of 3MWh conventional generation displaced by ACG at peak times is estimated to be £600. Therefore, £300 would be saved through the time-shifting of ACG enabled by the BESS in a full cycle. As the BESS is expected to complete 300 cycles in a year, the cost of total ACG export, i.e. 1.2GWh used to charge the BESS is around £90,000. The cost of total conventional generation displaced by ACG, i.e. 0.9GWh is around £180,000 in a year. Approximately £90,000 would be therefore saved per annum if the battery completes the expected 300 cycles at 75% efficiency.

If the regular operation of the 1MW, 3MWh VRLA BESS commenced today, the BESS would be scheduled by the real-time algorithm to alleviate the ACG curtailment, mainly for Garth and Luggies Knowe wind farms. If the BESS is maintained at 75% efficiency, approximately £90,000 savings would be achieved per annum through 300 full discharge/charge cycles of the battery. Figure 17 compares the savings with the project replication costs within 15 years. Figure 18 shows the percentages of savings against the project replication costs in 15 years increase with time and may reach approximately 27% at the end of the 15th year.

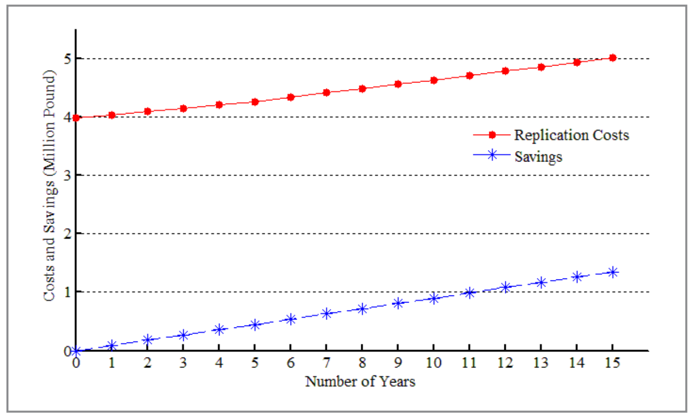

Figure 17 Comparison of the project replication costs and the savings by the time-shifting of ACG.

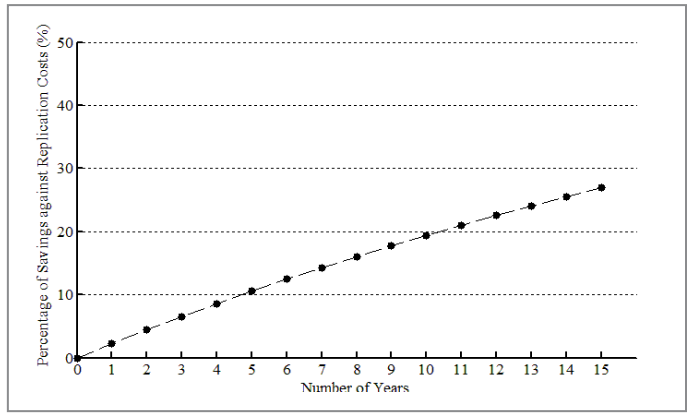

Figure 18 Percentage of the savings by the time-shifting of ACG against the project replication costs.

The majority of the conventional generation cost is fuel consumption. The fuel prices have been much lower recently since a sharp fall in oil prices in late 2014 triggered by the United States (US) shale revolution [22]. The average price for Brent oil was $43.74/barrel for the year 2016 and is predicted to increase to approximately $57.10/barrel for the year 2018 according to Short-Term Energy Outlook released by US Energy Information Administration in April 2017 [23]. The 30.54% growth in the fuel price would largely increase the benefits of the time-shifting of ACG enabled by the BESS. As the fuel usage is the major component of the conventional generation cost, the average cost of conventional generation is estimated to be approximately £261/MWh (i.e. £200/MWh x 130.54%). Therefore, the cost of 3MWh conventional generation displaced by ACG at peak times is around £783 and £483 would be saved in a full cycle of the BESS. If the fuel price is maintained at this level in the following 15 years, approximately £144,900 would be saved per annum if the expected 300 full cycles are completed per annum. Therefore, the total savings in 15 years would reach 43.4% of the total project replication cost. According to World Bank Commodities Price Forecast [24], the annual average oil price will continually increase at an average annual growth rate of approximately 2.5% beyond the year 2018. The continuous growth in fuel prices would lead to a further saving in the conventional generation cost through the time-shifting of ACG.

5.4.4 Battery cost – benefit analysis

As calculated in Section 5.4.1 approximately 52.7MWh ACG curtailment had been alleviated by charging the battery over the period from September 2015 to November 2016. The volume of reduction in ACG curtailment is relatively small compared with the total import of the BESS over the evaluated period due to that only 0.5MW ACG was connected until February 2016 and that the BESS was not directly scheduled to alleviate ACG constraint during the period under review. This would lead to an exorbitant cost of using the BESS to alleviate ACG curtailment as detailed in Commercial Arrangements Report.

As was noted above, with the real-time control algorithm and the increase in ACG capacity to 8.5MW, all the energy used to charge the BESS may be supplied by ACG which would otherwise be curtailed. Therefore, approximately 1.2GWh of ACG curtailment would be alleviated based on the BESS completing the expected 300 cycles per annum. Considering an approximate lifetime of 15 years, 18GWh of ACG curtailment would be reduced by the operation of the BESS. As the project replication cost is estimated to reach £5,006,500 at the end of the 15th year, the cost of using the 1MW, 3MWh BESS to alleviate renewable energy curtailment would be approximately £278.14/MWh if the regular operation of the BESS commenced today.

Based on an estimated average cost £200/MWh of conventional generation, the time-shifting of 4MWh ACG enabled by the BESS was evaluated to save approximately £300 in a full cycle, i.e. £75/MWh through displacing conventional generation at peak times. Taking account of the benefit with respect to the time-shifting of ACG, the net cost of using the BESS to alleviate ACG curtailment is £203.14/MWh. If the forecast of 30.54% growth in the fuel price is additionally considered, approximately £483 would be saved per full cycle, i.e. £120.75/MWh, and the net cost of alleviating ACG curtailment will be reduced to £157.39/MWh.

6

Reductions in conventional generation

6. Reductions in conventional generation

The 1MW, 3MWh VRLA BESS at LPS plays an important role in the time-shifting of conventional generation and renewable energy. As illustrated in Figure 5, the conventional generation used to charge the battery at times of low demand was injected into the grid at peak times but with a round-trip efficiency of 75%. The time-shifting of conventional generation would increase the efficiency of lightly loaded engine sets at LPS at times and reduce the peak demand to be met by conventional generation. Furthermore, as discussed in Section 5, the electricity absorbed by the BESS was sometimes supplied by ACG. When the new real-time algorithm is implemented to charge the battery at the times the ACG is curtailed, it may allow more renewable generation to be stored in the BESS during the off-peak and then to be discharged at the following peak times.

6.1 Savings by Time-shifting of Conventional Generation

Over the period from September 2014 to November 2016, the total import and export of the BESS at LPS were 1.77GWh and 1.34GWh respectively. The savings (£) in conventional generation costs provided by the time-shifting of conventional generation can be determined as the difference between the expenditure for the conventional generation plant providing the energy equal to the reduction in system demand at peak times and the expenditure for the conventional generation used to charge the battery at off-peak times. Given that 52.7MWh ACG used to charge the BESS was converted into 37.5MWh discharged energy, the BESS absorbed 1.72GWh from conventional generation which was converted to 1.30GWh discharged energy in total. Given the cost per unit of conventional generation at peak times $£_{peak}$ and that for off-peak times $£_{off}$, the savings in conventional generation cost through the time-shifting of conventional generation can be estimated as:

$$\text{Savings}_{conventional} = 1.30\text{GWh}\times£_{peak} - 1.72\text{GWh}\times£_{off} \quad (13)$$

where a positive savings associated with the time-shifting of conventional generation $Savings_{conventional}$ would be achieved if $£_{peak} > 1.33\ £_{off}$. Note this is not how the arrangements currently work, but the savings in conventional generation costs may have been realised through the time-shifting of the conventional generation if $£_{peak} > 1.33£_{off}$ is fulfilled. This may be considered in the future arrangements.

6.2 Savings by Time-Shifting of Renewable Generation

As calculated in Section 5.4, the BESS absorbed 52.7MWh ACG export which would otherwise be curtailed over the period from September 2015 to November 2016. The 52.7MWh ACG used to charge the battery had been converted into 37.5MWh discharged energy considering the BESS was cycled at 75% efficiency. The time-shifting of the 52.7MWh ACG provided approximately £794.29 savings.

When the real-time algorithm is used to determine the schedules for the battery, all the energy used to charge the battery may be supplied by additional ACG export, mainly from Garth and Knowe which would otherwise be curtailed. It has been evaluated that 3MWh (£600) conventional generation would be reduced at peaks by the time-shifting of 4MWh (£300) ACG in a full discharge/charge cycle, leading to approximately £300 savings. If the battery is expected to complete 300 full cycles per annum, the time-shifting of 1.2 GWh ACG would reduce 0.9GWh conventional generation and provide a total saving of £90,000 in a year. Considering a projected growth of 30.54% in average annual oil price from 2016 to 2018 [23], the average cost per MWh of conventional generation increases to around £261/MWh. The total saving achieved by the time-shifting of 1.2GWh ACG per annum would then increase to £144,900.

Though conventional generation are reduced by up to 1MW, 3MWh at peak times the conventional generation plant may still be running as spinning reserve. This is because the 1MW output from the BESS is not large enough to prevent the start-up of an engine to cover the peak demand. The cost of engines running as spinning reserve has been included in the estimated cost £200/MWh of conventional generation however there will be a reduction in fuel usage.

7

Reactive Power Support by BESS

7. Reactive Power Support by BESS

Scottish & Southern Electricity Networks

The grid has to provide reactive power for the operation of inductive electrical loads such as motors and transformers. Otherwise, the absorption of reactive power by the inductive loads would lower the power factor and thus lead to a higher current passing through the line in order to supply the desired active power. Reactive power compensation can therefore maintain the power factor on the bus to mitigate transmission losses and minimise the voltage drop across the line, keeping the node voltage within an acceptable range [25].

Conventionally, switched or static shunt capacitors installed on the bus provide a cost-effective way to effectively provide reactive power which is consumed by the inductive loads. However, these shunt capacitor banks have the disadvantages of large switching transients and the nature of "all-or-nothing" [25]. An on-grid BESS, by contrast, is capable of delivering and consuming reactive power at a continuously varying rate [25] during both charging and discharging phases. The waveform of current injected into or absorbed from the grid can be modulated by a power conversion system (PCS) that connects the battery bank to the grid, while the node voltage will be adjusted to the required level by a tap-changing transformer [1]. The electronic converters that are capable of four quadrant power [26] enable the BESS to provide active power and reactive power at any expected ratio, as shown in Figure 19. In addition to the BESS, the Enercon turbines installed through the NINES project [27] are required to operate in voltage support mode and may also absorb or deliver reactive powers as required.

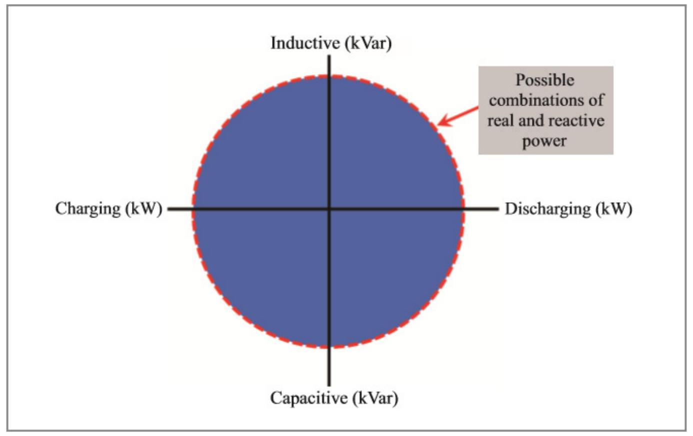

Figure 19 P-Q diagram representing the four-quadrant operation of a BESS [26]

The BESS installed at LPS having a 1MW, 1.25MVA PCS [8] can deliver and absorb a maximum of 1MW active power and 0.75MVar reactive power evaluated at 1MW. In order to assess the BESS's capability of regulating the voltage of the node it is connected to through reactive power compensation we compare the node voltages (in p.u.) of two cases (a) when the BESS is allowed to provide the reactive power support within ±0.75MVar and (b) when the reactive power output from the BESS is zero.

Calculations of power flow when the BESS injects 1MW into the Shetland network with a total demand of around 40MW, 41MVA were analysed by PSS/E software [28]. It was found that the voltage of the node connecting the BESS increases from 0.97p.u. to 1p.u. when the BESS delivers 0.64MVar reactive power to the grid. Therefore, it may be feasible to use the BESS to provide the reactive power support to adapt the voltage at the local node.

8

Conclusions

8. Conclusions

The report has reviewed the energy storage technologies and analysed the operational effectiveness of a grid-scale Valve Regulated Lead-Acid (VRLA) Battery Energy Storage System (BESS) on the Shetland network, mainly with respect to the utilisation of the BESS operating under different schedules and how the BESS promotes the connection of renewable generation. The 1MW, 3MWh BESS had completed 288 cycles and discharged 629.7MWh in the first full year demonstrating 96% of the expected 300 cycles per annum and approximately 70% utilisation of the BESS were achieved.

Under Active Network Management (ANM) calculated schedules and manually derived schedules, the utilisations of battery were estimated to be about 47.2% and 86.1% respectively in the first full year. For the majority of its operation, the BESS was manually scheduled to discharge at peak times and charge during the off-peaks, which smoothed the demand curve of the network. The total import and export of the BESS over more than two years from September 2014 to November 2016 were around 1.34GWh and 1.77GWh respectively. The difference between import and export was the volume of energy losses approximately equal to 0.43GWh, which was less than the theoretical estimate due to that the actual round-trip efficiency on average was 0.7% higher than an approximate efficiency of 75%.

The output of non-firm distributed generation, i.e., ANM Controlled Generation (ACG), was controlled by a set of constraint rules (CTRs) that were designed to preserve the stability of the Shetland network. Charging the battery can increase the limit on ACG output and enable ACG to deliver additional power to the network if there was ACG curtailment without the BESS being charged. Over the period from September 2015 to November 2016 where the up-to-date CTRs were implemented, approximately 52.7MWh of additional ACG export was enabled by charging the battery although the manual schedule was not optimised for this objective.

A new real-time algorithm has been developed to schedule the battery to charge at the times ACG is curtailed. The charge rate would be equal to the lower value from the ACG curtailment or the maximum rate dependent on the SOC of battery. Based on a series of historic data at off-peak times where ACG was curtailed for majority of the time, the real-time algorithm was evaluated to schedule the BESS to absorb the electricity from additional ACG export which would otherwise be curtailed. The advantage of the real-time algorithm may be exploited fully as the total capacity of ACG increased to 8.5MW under NINES in March 2017. With the real-time algorithm and the increase in ACG capacity, 1.2GWh additional ACG export may be absorbed by the BESS and then converted into 0.9GWh energy delivered to the grid at peak times each year if completes its expected 300 full cycles per annum.

At the current fuel price it is evaluated that £90,000 savings may be achieved per annum by using the time-shifting of ACG to reduce conventional generation. The £75/MWh of savings associated with the time-shifting of ACG would result in a net cost of using the BESS to alleviate renewable curtailment equal to £203.14/MWh. The percentage of total savings against the replication costs of the BESS which enabled the time-shifting of ACG is evaluated to increase with time and may reach approximately 27% at the end of the 15th year. Considering a forecast growth of 30.54% in annual average oil prices from 2016 to 2018, the costs of conventional generation displaced by ACG would increase and the saving achieved by the time-shifting of ACG then increases to £144,900 per annum which reduces the net cost of alleviating ACG curtailment to £157.39/MWh. At the projected annual average oil price the total saving is evaluated to reach approximately 43.4% of the total project replication cost in 15 years.

The report contributes to Learning Outcomes by helping to answer the following questions:

- *How can a distribution system be securely operated with a high penetration of renewable generation?*

A set of constraint rules managed by an ANM system has been set up to preserve the stability of the Shetland network operating with a higher penetration of renewable generation.

With the integration of a BESS on the network, it has been shown in Section 5 that the BESS is capable of absorbing excess renewable generation that would otherwise be constrained.

- *What is the relationship between intermittent generation and responsive demand, including storage?*

  a. Effectiveness of frequency response demand side management
  b. Maintaining network stability in an operational environment
  c. Interaction of numerous variables on a closed electrical system

As introduced in Section 5, the export of intermittent generation is limited by constraint rules. The fast-acting SVT export will be reduced to accommodate high outputs from ACG, which may violate the minimum-take export limit of SVT. The BESS can help accommodate high ACG export by absorbing the ACG power which would otherwise be curtailed. Though the manual schedule is not optimised for this, it has enabled around 52.7MWh of additional ACG export during the off-peak over the period from September 2015 to November 2016. With a large increase in ACG capacity and a new real-time algorithm developed by SSEN to charge the battery in response to ACG curtailment, the BESS will play an important role in promoting the utilisation of intermittent generation.

- *What is the impact of the low carbon network on domestic and industrial customers?*

  a. Effect on fuel poverty
  b. Changes in attitudes, awareness and behaviour amongst customers
  c. Extent of financial impact on participants

As introduced in Section 3, the grid-scale BESS at Lerwick Power Station was scheduled with the primary aim to discharge at peak times and charge at times of low demand, which smoothed the demand curve of the Shetland network. This led to flatter power outputs and thus a more efficient operation of conventional generation units. Furthermore, at times the energy used to charge the BESS was supplied by additional export of ACG which would otherwise be curtailed. When the real-time control algorithm is implemented, the energy absorbed by the BESS may be primarily supplied by ACG. The ACG export stored in the BESS will then be injected into the network at peak times to reduce the demand to be met by conventional generation. The time-shifting of conventional generation and intermittent generation enabled by the BESS will reduce fuel consumption and generation costs of conventional generation plant. Furthermore, additional export of ACG enabled by the BESS which would otherwise be curtailed will increase the financial benefits to ACG owners.

- *To what extent do the new arrangements*

  a. Stimulate the development of, and connection to, the network of more renewable generation?
  b. Reduce the area's reliance on fossil fuels?

As evaluated in Sections 5.3, the BESS operating under the real-time control algorithm may accommodate a higher level of ACG export which would otherwise be curtailed. With the total capacity of ACG on the network now increased to 8.5MW, the advantage of the real-time algorithm in reducing the ACG curtailment may be fully realised. The ACG export absorbed and stored by the BESS will be delivered back to the network at peak times subject to a round-trip efficiency of 75%. The time-shifting of renewable generation enabled by the BESS will reduce the reliance on fossil fuels.

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